PB87-171278

Underground Storage Tank Corrective Action Technologies

PEI Associates, Inc., Cincinnati, OH

Prepared for

Environmental Protection Agency, Cincinnati, OH

Jan 87

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA/625/6-87/015	2.	3. RECIPIENT'S ACCESSION NO. PB87 171278/AS
4. TITLE AND SUBTITLE Underground Storage Tank Corrective Action Technologies		5. REPORT DATE January 1987
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Robert Cochran et al.		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS PEI Associates Chester Towers Cincinnati, Ohio 45268		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. 68-02-3995
12. SPONSORING AGENCY NAME AND ADDRESS Hazardous Waste Engineering Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Final, 1/86-12/86
		14. SPONSORING AGENCY CODE EPA/600/12

15. SUPPLEMENTARY NOTES

Project Officer: Douglas C. Ammon (513) 569-7876

16. ABSTRACT

This document contains information on corrective action technologies for releases from underground storage tanks (UST). It probes general background information on UST contruction techniques, leak detection methods, and failure mechanisms. It also addresses transport pathways of released substances, techniques for evaluating the extent of a release, factors influencing risk to human health and the environment, techniques for selecting initial corrective-action response technologies, and detailed technical profiles of corrective-action technologies. Emphasis is on corrective actions associated with releases from gasoline and petroleum USTS.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 205
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

United States
Environmental Protection
Agency

Hazardous Waste Engineering
Research Laboratory
Cincinnati OH 45268

Office of Solid Waste and
Emergency Response
Washington DC 20460

EPA/625/6-87-015
January 1987

PB87-171278

Technology Transfer

EPA

Underground Storage Tank Corrective Action Technologies

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL
INFORMATION SERVICE
SPRINGFIELD, VA 22161

EPA 625/6-87/015
January 1987

Underground Storage Tank Corrective Action Technologies

Hazardous Waste Engineering Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

Office of Underground Storage Tanks
Office of Solid Waste and Emergency Response
U.S. Environmental Protection Agency
Washington, D.C. 20460

i.a

Notice

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Abstract

Several factors influence the decision maker's selection of a path of corrective action for dealing with a leaking underground storage tank (UST). This document provides information to assist in the scientific and technical direction of the response efforts. It probes general background information on UST construction techniques, leak detection methods, and failure mechanisms. It also addresses transport pathways of released substances, techniques for evaluating the extent of a release, factors influencing risk to human health and the environment, techniques for selecting initial corrective-action response technologies, and detailed technical profiles of corrective-action technologies. Emphasis is on corrective actions associated with releases from gasoline and petroleum USTs; however, profiles are also provided for technologies used in response to chemical releases.

Responses to UST releases generally involve consideration of two steps: 1) initial corrective actions (source control), and 2) permanent corrective actions. The degree of detail and amount of resources applied in these steps depends on site-specific conditions, such as the volume of the release, the time frame within which the release occurred, hydrogeologic conditions, and the proximity to environmentally sensitive communities and human receptors.

The characterization and assessment of an UST release usually include the following: ascertaining the release mechanism, determining the extent of release (volume and release rate), and evaluating transport pathways (air, surface water, and ground water). Site characteristics are important in the assessment of the rate of transport to receptor communities, the evaluation of the effects of releases on receptor communities, and the analysis of the effects of initial and corrective-action responses on receptor populations.

The initial corrective actions to mitigate a leaking UST will almost certainly involve removal of the product from the tank and either tank repair or removal. It also may be necessary to contain, treat, or remove any substance released to the environment. The case studies contained in this document offer examples of the technologies often used to mitigate the effects of leaking USTs. The selection of more permanent corrective measures requires a higher level of analysis and may involve the use of more sophisticated technologies. This document identifies and describes technologies that have been used during a permanent corrective action response. Technology selection requires a detailed analysis of site-specific conditions and the establishment of cleanup goals and objectives.

This report was submitted in partial fulfillment of Contract No. 68-02-3995 by PEI Associates, Inc., under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period from January 1986 to December 1986, and work was completed as of December 1986.

Contents

Page

Abstract iii

Figures viii

Tables xi

Acknowledgments xiv

1. Introduction 1-1

    1.1 Background 1-1
    1.2 Objective 1-2

2. Underground Storage Tank Design 2-1

    2.1 Types of Underground Storage Tanks 2-1
    2.2 Failure Modes 2-5

3. Leak Detection and Environmental Assessment 3-1

    3.1 Tank Monitoring 3-1
        3.1.1 Leak test technologies 3-1
        3.1.2 Leak detection variables 3-7

    3.2 Contaminant Migration (Transport) Pathways 3-8
        3.2.1 Unsaturated zone (Vadose Zone) 3-8
        3.2.2 Capillary zone 3-9
        3.2.3 Saturated zone 3-11
        3.2.4 Vapor phase transport 3-11

    3.3 Initial Assessment of Extent of Release 3-12
        3.3.1 Existing sampling points 3-12
        3.3.2 New sampling points 3-13

4. Corrective Action Response Process 4-1

    4.1 Initial Corrective-Action Options 4-1
        4.1.1 Evaluation of release 4-1
        4.1.2 Initial corrective actions 4-6

    4.2 Permanent Corrective-Action Options 4-6
        4.2.1 Assessment and investigation to determine surrounding land use and potential impact on public health 4-6

        4.2.2 Factors affecting selection of corrective actions 4-6

    4.3 Risk Analysis 4-9

Preceding page blank

5. Technology Profiles 5-1

5.1 Tank Removal, Abandonment, and Rehabilitation Removal/Excavation of Soil and Sediments 5-4
  5.1.1 Tank removal, abandonment, and rehabilitation 5-4
  5.1.2 Soil excavation 5-6
  5.1.3 Sediment removal 5-7

5.2 Onsite and Offsite Treatment and Disposal of Contaminants 5-8
  5.2.1 Solidification/stabilization 5-8
  5.2.2 Landfilling 5-9
  5.2.3 Landfarming 5-11
  5.2.4 Soil washing 5-11
  5.2.5 Thermal destruction 5-12
  5.2.6 Aqueous waste treatment 5-14
  5.2.7 Deep-well injection 5-14

5.3 Free Product Recovery 5-15
  5.3.1 Dual-pump systems 5-16
  5.3.2 Floating-filter pumps 5-18
  5.3.3 Surface oil/water separators 5-18

5.4 Ground-Water Recovery Systems 5-19
  5.4.1 Ground-water pumping 5-20
  5.4.2 Subsurface drains 5-34

5.5 Subsurface Barriers 5-39
  5.5.1 Slurry walls 5-39
  5.5.2 Grouting 5-46
  5.5.3 Sheet piles 5-47
  5.5.4 Hydraulic barriers 5-48

5.6 In Situ Treatment 5-50
  5.6.1 Soil flushing 5-50
  5.6.2 Biostimulation 5-52
  5.6.3 Chemical treatment 5-55
  5.6.4 Physical treatment 5-58

5.7 Ground-Water Treatment 5-58
  5.7.1 Air stripping 5-59
  5.7.2 Carbon adsorption 5-61
  5.7.3 Biological treatment 5-63
  5.7.4 Precipitation/flocculation/sedimentation 5-68
  5.7.5 Dissolved air flotation 5-72
  5.7.6 Granular media filtration 5-73
  5.7.7 Ion exchange/resin adsorption 5-75
  5.7.8 Oxidation/reduction 5-77
  5.7.9 Neutralization 5-78
  5.7.10 Steam stripping 5-79
  5.7.11 Reverse osmosis 5-81
  5.7.12 Sludge dewatering 5-84

5.8 Vapor Migration Control, Collection, and Treatment 5-90
  5.8.1 Passive collection systems 5-90
  5.8.2 Active vapor control 5-92
  5.8.3 Ventilation of structures 5-95
  5.8.4 Adsorption 5-95
  5.8.5 Flaring 5-96

5.9 Surface Water/Drainage Controls 5-97
  5.9.1 Diversion/collection systems 5-98
  5.9.2 Grading 5-101
  5.9.3 Capping 5-104
  5.9.4 Revegetation 5-105

5.10 Restoration of Contaminated Water Supplies and Utility/Sewer Lines 5-110
  5.10.1 Alternative central water supplies 5-110
  5.10.2 Alternative point-of-use water supplies 5-111
  5.10.3 Treatment of central water supplies 5-112
  5.10.4 Treatment of point-of-use water supplies 5-112
  5.10.5 Replacement of water and sewer lines 5-113
  5.10.6 Cleaning/restoration of waterlines and sewerlines 5-114

6. Reference Matrix for Case Histories 6-1

6.1 Purpose of Case Histories 6-1
6.2 Case History Matrix 6-2

References R-1

Appendix Case Histories A-1

Index I-1

Figures

Number		Page
2-1	Isometric of three tanks connected to one or more pumps	2-1
2-2	Typical anchoring systems where subsurface water conditions exist	2-3
2-3	Components for tank installations with suction pumping	2-4
2-4	Components for tank installations with submerged pumping	2-4
2-5	Piping arrangement of external pump	2-5
3-1	Diagram of typical subsurface environment of USTs	3-8
3-2	Shape of hydrocarbon plume in vadose zone under different leakage rates and physical conditions	3-9
3-3	Typical flow pattern for hydrocarbons in the capillary zone	3-10
3-4	Typical behavior of hydrocarbons in soil following a sudden high-volume release	3-10
3-5	Behavior of hydrocarbons after release has stabilized	3-11
4-1	Typical initial corrective-action process	4-1
4-2	Site information needs for evaluation of corrective-action alternatives	4-4
4-3	Potential initial response situations and associated corrective actions	4-7
4-4	Permanent corrective-action process	4-7
4-5	Matrix of permanent corrective action categories for specific site problems	4-8
5-1	Flow chart of activities involved in the initial response to an UST release	5-1
5-2	Flow chart of permanent corrective action in response to an UST release	5-2
5-3	Potentially applicable corrective action technologies relative to release volume and chemical characteristics	5-3
5-4	Flow diagram for EPA mobile soil washer	5-12

5-5 Diagram of a conventional industrial injection well completed in sandstone 5-15
5-6 Dual-pump recovery system 5-16
5-7 Floating-filter recovery system 5-18
5-8 Oil/water separator 5-19
5-9 Containment by the use of extraction wells 5-20
5-10 Extraction and injection well patterns for plume removal 5-21
5-11 Plume diversion using injection wells 5-22
5-12 Suction wells 5-24
5-13 Multiple suction lift wells (Well point system) 5-25
5-14 Submersible pump 5-25
5-15 Downhole turbine 5-26
5-16 Deep well jet pump 5-26
5-17 Variations of ejector wells 5-27
5-18 Single-pipe ejector 5-27
5-19 Types of wells 5-28
5-20 Subsurface drainage system components 5-34
5-21 Use of a one-sided subsurface drain for reducing flow from uncontaminated sources 5-35
5-22 The effect of relief and interceptor drains in altering the configuration of the water table 5-36
5-23 Subsurface drain with a lift station 5-36
5-24 Typical design of an automatic drainage pumping plant 5-37
5-25 Slurry trench construction 5-44
5-26 Slurry wall placement 5-45
5-27 Semicircular grout curtain 5-47
5-28 Typical steel piling shapes and interlocks 5-49
5-29 Soil flushing system 5-50
5-30 Biostimulation of soil and ground water 5-52
5-31 Air-stripping equipment configurations 5-60

5-32 Annual cost for air stripping 5-61

5-33 Two-vessel granular carbon adsorption system 5-62

5-34 Estimated costs of various sizes of activated carbon adsorption units 5-63

5-35 Representative configuration employing precipitation, flocculation, and sedimentation 5-68

5-36 Solubility of metal hydroxides and sulfides 5-68

5-37 Representative types of sedimentation 5-70

5-38 Capital and annual O&M costs for flocculation 5-71

5-39 Dissolved air flotation system 5-72

5-40 Capital and annual O&M costs for dissolved air flotation 5-73

5-41 Example granular media filtration bed 5-74

5-42 Pertinent features of ion exchange systems 5-76

5-43 Construction and annual O&M costs for ion exchange 5-77

5-44 Construction and annual O&M costs for chemical oxidation and reduction 5-78

5-45 Construction and annual O&M costs for neutralization 5-79

5-46 Steam stripping system 5-80

5-47 Capital and annual O&M costs for steam stripping 5-81

5-48 Reverse osmosis membrane module configurations 5-83

5-49 Concentration and annual O&M costs for reverse osmosis 5-84

5-50 Drum-type rotary vacuum filter 5-84

5-51 Filter press plate 5-85

5-52 Belt filter press 5-86

5-53 Types of centrifuges 5-87

5-54 Capital and annual O&M costs for vacuum filters and filter presses 5-89

5-55 Capital and annual O&M costs for belt presses and centrifuges 5-89

5-56 High-permeability passive vapor control system 5-91

5-57 Low permeability passive vapor control system 5-92

5-58 Active vapor control system 5-93

6-1 Case history matrix 6-2

Tables

Number		Page
2-1	Underground tank installation practices	2-2
2-2	Comparison of containment systems for UST releases	2-6
3-1	Summary of volumetric leak detection methods	3-2
3-2	Summary of nonvolumetric leak detection methods	3-4
3-3	Summary of other leak detection methods	3-5
3-4	Variables affecting accuracy of leak detection	3-7
3-5	Typical values for Rv	3-9
3-6	Water monitoring techniques	3-14
4-1	Petroleum products stored in underground storage tanks	4-2
4-2	Selected chemicals (462) stored in underground storage tanks	4-3
5-1	Soil excavation costs	5-7
5-2	Solidification/stabilization processes	5-9
5-3	Solidification costs	5-9
5-4	Summary comparison of relative 1986 costs of stabilization/ solidification alternatives	5-10
5-5	Summary of commonly used incineration technologies	5-13
5-6	Approximate costs for hazardous waste incineration	5-14
5-7	Product recovery costs	5-17
5-8	Criteria for well selection	5-22
5-9	Common methods of well installation	5-29
5-10	1986 costs for selected pumps and accessories	5-31
5-11	1986 costs for well screens and wellpoints	5-32
5-12	1986 costs for completion of 2- to 4-inch diameter wells	5-32
5-13	Summary of seven recovery system cost scenarios	5-33

5-14 1986 unit costs for trench excavation and associated activities 5-40

5-15 1986 unit costs for pipe installation 5-42

5-16 1986 installed costs for manholes 5-43

5-17 Capital costs for interceptor drain installation 5-43

5-18 Costs of common grouts 5-47

5-19 Applicability of soil flushing techniques 5-51

5-20 Estimated costs for hypothetical bioreclamations with hydrogen peroxide as an oxygen source 5-55

5-21 Summary of in situ treatment methods 5-56

5-22 Estimated costs for in situ physical treatment methods 5-58

5-23 Applicability of ground-water treatment processes 5-59

5-24 Packed-column air stripping of volatile organics 5-59

5-25 Costs for packed-column aeration 5-61

5-26 General cost data for various sizes of activated-carbon adsorption units 5-63

5-27 Summary of applications/limitations of biological treatment process 5-65

5-28 Concentration of pollutants that make prebiological or primary treatment advisable 5-66

5-29 General cost data for various sizes of activated sludge treatment units 5-67

5-30 General cost data for various sizes of ion exchange units 5-77

5-31 Results of pilot scale testing of a reverse osmosis unit 5-81

5-32 1986 unit costs for components of passive vapor-control systems 5-92

5-33 Materials and equipment for active vapor-control systems 5-94

5-34 1986 unit costs for components of active vapor-control systems 5-94

5-35 1986 capital costs of elevated flares (for vapor with heat content of 60 Btu/ft^3) 5-97

5-36 Supplemental fuel requirements for elevated flares 5-97

5-37 Summary of surface water/drainage controls 5-98

5-38 1986 unit costs associated with surface water diversion and collection structures 5-102

5-39 1986 unit costs associated with grading 5-104

5-40	1986 unit costs associated with capping	5-106
5-41	Important characteristics of grasses and legumes	5-107
5-42	1986 unit costs associated with revegetation	5-109
5-43	1986 unit costs for replacement of water and sewer lines	5-113

Acknowledgment

This document was prepared for EPA's Office of Research and Development, Hazardous Waste Engineering Research Laboratory, in partial fulfillment of contract No. 68-02-3995. Mr. Douglas Ammon served as the EPA Technical Monitor and directed the technical efforts of the project. Technical assistance was supplied by Mr. John Hefflefinger, Office of Underground Storage Tanks, Mr. Jack Farlow and David Berg, Office of Research and Development, and Mr. William Foskett, consultant. Clarence Clemons, Dale Dietrich, and Norm Kulujian, Center for Environmental Research Information, are acknowledged for their technical and editorial assistance. Mr. Jack Greber served as PEI Associates Project Director and Mr. Bob Cochran served as PEI Associates Project Manager. Other major contributors include Ms. Judy McArdle, Mr. Fred Hall, Mr. Bill Trapp, Ms. Barb Locke, Mr. Doug Bailey, Ms. Catherine d. C. Hartman, Mr. Don Henz, Mr. Bill Thompson, and Ms. Jan Zieleniewski. We are particularly grateful for the substantial contributions of the Technical Editor, Ms. Marty Phillips, and of the Copy Editor, Mr. Jerry Day. Great appreciation is extended to the following peer reviewers and contributors:

• Dr. David Chin	American Petroleum Institute
• Dr. Rudy White	American Petroleum Institute
• Mr. Jeffrey Reame	Chemical Manufacturers Association
• Ms. Anne Mason	Chemical Manufacturers Association
• Dr. Jay Lehr	National Water Well Association
• Mr. Hari Bindal	Department of the Air Force
• Mr. Jeff van Ee	U.S. Environmental Protection Agency
• Mr. Jerry Jones	U.S. Environmental Protection Agency
• Mr. Kevin Smolenyak	Clark Engineers and Scientists

We would also like to acknowledge the contributions of the PEI graphics and typing staff, Ms. Marty Gillaspy, Ms. Stephanie Gresham, and Ms. Connie Hutchinson, for their contribution in producing the document.

Section 1
Introduction

1.1 Background

Somewhere between three and five million underground tanks in the United States are used to store liquid petroleum and chemical substances. Estimates indicate that 100,000 to 400,000 of these tanks and their associated piping systems may be leaking. The large percentage of these underground storage tanks that contain petroleum products are of particular concern. Recent studies also indicate that, if these leaks are left unattended, their number will likely increase, and releases from these sources can result in the contamination of subsurface soils, the migration of toxic or explosive vapors, and the contamination of ground- and surface-water systems. Environmental and tank monitoring, tank replacement, and corrective action technologies can reduce the potential of future releases or remedy the effects of prior releases from underground storage tanks.

Industry sources estimate that the average cost of tank cleanup at a site is about $70,000; however, if tank removal and treatment of surrounding soils are required, these costs can total more than $1 million. Should underground tank leakage impact ground water, surface water, drinking water supplies, reservoirs, sewers, or utility trenches, the costs of corrective action can quickly reach well beyond the $1-million range. The extent of resources required for corrective action depends on the magnitude of release, the toxicity of the substance, and the agreed-upon level or objective of the proposed cleanup.

Concern for the status of underground storage tanks has prompted the development of legislation regarding the registration and monitoring of existing tanks, design and installation of new tanks, and corrective actions for releases. The 1984 Hazardous and Solid Waste Amendments (HSWA) to the Resource Conservation and Recovery Act (RCRA) added a new Subtitle I, "Regulation of Underground Storage Tanks." Subtitle I requires the U.S. Environmental Protection Agency (EPA) to develop a comprehensive program for regulating certain underground storage tanks that contain regulated substances. Section 9001(1) defines an "underground storage tank" as:

> "...any one or combination of tanks (including underground pipes connected thereto) which is used to contain an accumulation of regulated substances, and the volume of which (including the volume of the underground pipes connected thereto) is ten percent or more beneath the surface of the ground."

The definition does not include noncommercial farm or residential motor fuel tanks with capacities of less than 1100 gallons, heating oil tanks, septic tanks, flowthrough process tanks, and gas and oil production lines.

Section 9001(2) defines "regulated substances" as:

> "(A) any substance defined in Section 101(4) of the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (but not including any substances regulated as a hazardous waste under Subtitle C), and
>
> (B) petroleum, including crude oil or any fraction thereof which is liquid at standard conditions of temperature and pressure (60 degrees Fahrenheit and 14.7 pounds per square inch absolute)."

In Subtitle I, Congress requires the EPA Administrator to promulgate underground storage tank regulations "as may be necessary to protect human health and the environment" [Section 9003(a)]. The EPA is responsible for developing "requirements for taking corrective action response to a release from an underground storage tank" [Section 9003(c)(4)] and "requirements for reporting of releases and corrective action taken in response to a release from an underground storage tank" [Section 9003(c)(3)]. Section 9001(5) defines "release" as "any spilling, leaking, emitting, discharging, escaping, leaching, or disposing from an underground storage tank into ground water, surface water, or subsurface soils." "Corrective action" is not defined in Subtitle I, although the term is used to describe actions carried out in response to releases from underground storage tanks.

As of December 1986, EPA is evaluating proposed regulations for underground storage tanks. These proposed regulations will require that owners and operators take corrective actions to remedy releases from underground storage tanks. They will most likely require immediate corrective action to reduce fire and explosion hazards and to recover free product and remove contaminated soils. In addition, they probably will require that these immediate responses be followed by longer-term corrective actions when such actions are necessary to address ground-water contamination.

1.2 Objective

The EPA's newly formed Office of Underground Storage Tanks (OUST), which is part of the Office of Solid Waste and Emergency Response, is responsible for establishing the Agency's regulatory program for controlling underground storage tanks. The Hazardous Waste Engineering Research Laboratory (HWERL) of EPA's Office of Research and Development is responsible for providing engineering and scientific support to OUST. The objective of this effort is to establish a forum for technology transfer among the various regulatory agencies and the user community. To this end, this document contains information for determination of the state of the art, applicability, cost, and effectiveness of alternative corrective actions for leaking underground storage tanks (USTs).

This report presents profiles on technologies currently being used to correct leaking USTs. As part of this study, technologies or practices used in other environmental remediation programs (e.g., Superfund Remedial Actions) were analyzed to determine their cross-over potential for UST corrective actions.

Focus in this document is on the problems associated with underground storage tanks containing gasoline and petroleum products because 1) most of the USTs in the United States are designed and used for storing gasoline and petroleum products, and 2) technical information on releases of chemicals listed as Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) hazardous substances is available through the Superfund program technical literature.

Section 2 describes the design and construction materials of typical USTs. It contains a brief summary of the types of storage tanks and piping systems currently in use and the most commonly occurring tank failure modes and release events.

Section 3 describes methods and practices used to assess the integrity of tank systems and to determine the extent of any releases. The focus is on tank testing devices and methods for the speedy assessment of the extent of release and the determination of immediate environmental and public health impacts. The contaminant's fate and transport pathways are also summarized.

Section 4 presents methodologies for possible use in selecting the appropriate corrective-action-response alternative. The brief guidance on selection techniques concerns those applicable to initial response technologies (rapid response) and long-term corrective action remedies. The section also presents information on the types of site characterization data necessary for the selection, design, and implementation of permanent remedies. Data also include the chemical and physical properties of release substances and their impact on the selection of corrective-action technologies.

Section 5 contains a detailed discussion of the technologies surveyed, including descriptions of application and availability, design and construction considerations, ranges of unit costs, and additional reference materials.

Section 6 summarizes case history information. It includes a matrix that cross-references case history information with items critical to the selection and implementation of corrective-action technologies. Actual case histories are presented in the Appendix.

Section 2
Underground Storage Tank Design

The intent of this section is to familiarize the reader with the design features of underground storage systems. This information will help to establish a base for examining these systems in the field.

The configurations of the thousands of underground storage tanks in this country vary to suit several constraints, including the geography of the site, the type of material stored, insurance underwriter requirements, and the owner's operation. Regardless of the original design criteria, each installation will probably have these basic components:

- One or more tanks
- Antiflotation anchorage (in regions having high ground-water tables)
- Piping system
- Pumps
- Means for level gaging
- System for corrosion protection (if tanks are metal)

Tanks are usually placed underground to store materials that are classed as hazardous because of their flammability or combustibility. Many tanks were installed underground on the premise that they would never develop leaks, and little consideration was given to the consequences if any leakage should develop.

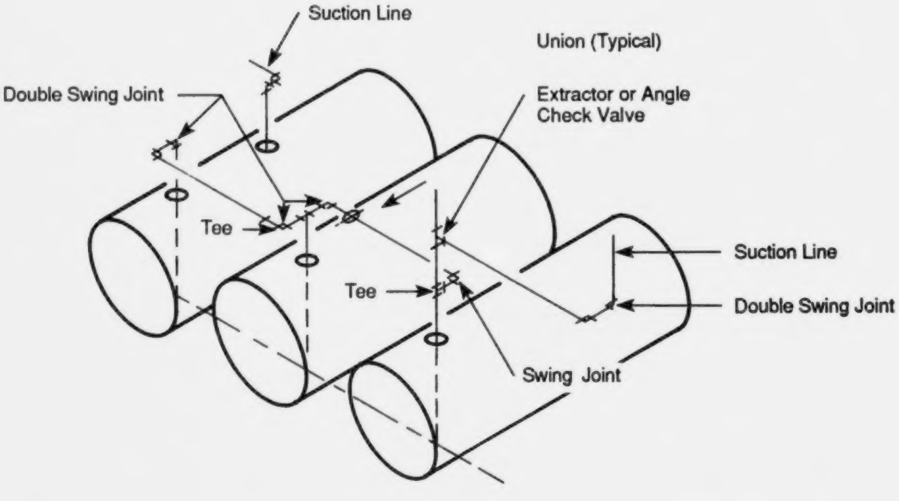
2.1 Types of Underground Storage Tanks

Two broad categories of underground tank applications are gas station and industrial/commercial installations. Underground tanks in gasoline stations are used for storage of the following products:

- Gasoline--leaded, unleaded, and premium grades
- Diesel oil
- Waste oil (may contain some gasoline)

Most gasoline stations have paved service areas; therefore, many of these tanks are located under pavement. Depending on the station's business volume, multiple tank installations (as shown in Figure 2-1) are often used. In gasoline stations, the pump is usually part of the product meter/dispenser located on the service island (commonly referred to as "the pump"); however, submerged pumps are also used.

Figure 2-1. Isometric of three tanks connected to one or more pumps (API 1979).



Industrial/commercial underground tank installations store a wide variety of materials, including solvents and various hydrocarbons. Both new materials and waste products are often stored underground because their contents are hazardous or explosive. These installations usually have individual tanks for each stored material rather than multiple tanks connected by common pump suction piping. Piping for industrial storage installations is not always located below grade; instead, it is sometimes run on overhead racks. In commercial installations such as dry cleaning establishments, system piping into the building is generally below grade.

Underground tanks vary in size, shape, and materials of construction. Metal tanks are usually welded and have some kind of exterior coating for protection against corrosion. Tanks fabricated from fiberglass, epoxy, or other nonmetallic material, which are common in newer installations, generally require no coating for corrosion resistance. Newer installations also might have tanks with double-wall construction. The annular space between the walls is used in various ways to detect product leaks from the inner tank wall or ground-water leaks into the outer tank wall.

Proper installation of underground storage tanks is crucial to their remaining leak-free. Most major tank manufacturers warrant their tanks against failure only if they are installed and used in accordance with the manufacturer's instructions. Therefore, USTs should be installed in strict conformance with the manufacturer's recommendations.

Fiberglass and plastic tanks are more fragile than steel tanks, and thus require more careful handling during installation. Also, fiberglass and plastic tanks receive a substantial portion (as much as 90%) of their structural support from backfill and bedding materials; hence, proper installation is extremely important if tank failures are to be avoided. Table 2-1 presents a summary of installation practices for fiberglass-reinforced plastic (FRP) and steel tanks.

Depth of tank burial varies, but the tank top is generally not more than one tank diameter below finished grade. At some installations, tanks are placed

Table 2-1. Underground Tank Installation Practices[*]

	Minimum Recommended Dimension, in.†		
Item	FRP (Capacity <20,000 gal)	FRP (Capacity >20,000 gal)	Steel
Distance between adjacent tanks	18	24	12
Distance between tank and excavation sidewall	24	24	24
Thickness of compacted bedding	12	12	6
Top slab extension beyond tank	18	24	12
Maximum burial depth	84	84	1.5 tank diameters
Top slab thickness assuming 34,000 lb per axle load			
Reinforced concrete plus compacted backfill	24	42	24
Asphaltic concrete plus compacted backfill	36	48	26
Top slab thickness assuming no traffic			
Reinforced concrete plus compacted backfill	16	30	16
Anchor slab extension beyond tank (if required because of buoyancy)	18	24	18
Anchor slab thickness (if required because of buoyancy)	8	8	8

[*] Data from API 1979; NFPA 1981.
† Except as noted.

in mounds and only partially buried below grade; however, they usually have the same components as underground tanks. The ground above underground tanks is usually paved if any traffic will occur. Manholes, caps, or other hardware are provided to cover and protect tank appurtenances such as the fill connections and gage pipes. Some large tanks are equipped with a manhole to allow access into the tank.

Unless the water table is well below the tank excavation, underground tanks have an anchor system of some sort to prevent them from floating upward and out of the ground. Figure 2-2 shows diagrams of a screw or expandable type anchor, a deadman anchor, and a concrete slab anchor.

Most tanks are filled and emptied through connections on the top side of the tank. Because the geometry of underground tank installations precludes liquid transfer by gravity, pumps are required. These pumps will either be submerged in the tank or be located above ground at a spot remote to the tank to supply material from the tank to the user (Figures 2-3 and 2-4). In these arrangements, one submerged pump is required for each tank, whereas an external pump can draw from more than one tank, as shown in Figure 2-5. Installations rarely have supply pumps connected to the tank bottoms because such an arrangement has the potential for complete loss of tank contents if the pump suction piping should fail.

Underground storage tanks generally include a method for tracking tank inventory, such as the use of a level gage. The most common level gage for underground tanks is a metering stick inserted in the fill tube. More elaborate systems might include bubbler-type pneumatic level sensors or a differential pressure instrument, which requires connections to the top and bottom of the tank.

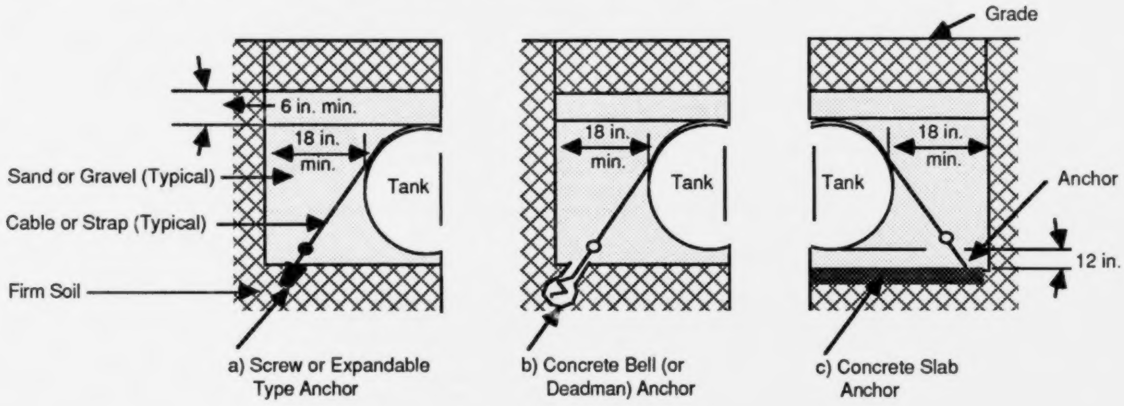
For metal tanks, systems for protection against corrosion are necessary to prevent piping or tank failures (leaks). Cathodic protection is commonly used. Other protection systems might be nothing more than a coating of mastic on the tank and the wrapping or taping of the underground piping.

Containment systems for releases from USTs represent the second line of defense against the propagation of soil or ground-water contamination. They also enhance the effectiveness of early-warning leak-monitoring systems by confining the release prior to its detection. The control technology used to contain underground releases consists of establishing a barrier around the storage tank to prevent the escape of the leaked liquid from the immediate area. The following barrier materials are used for containment:

- Liner with low soil permeability
- Synthetic membrane liners
- Soil cement or bentonites
- Concrete vaults
- Double walled tanks

The selection of the proper containment material for a particular application depends upon several factors, including the type of material being stored, local environmental conditions, and legislative requirements. The containment system should be sloped to a sump, from which a sample can be taken for analysis. It also should have a siphoning or pumping system capable of removing the liquids contained within the system. Table 2-2 presents a comparison of containment systems for UST releases.

Figure 2-2. Typical anchoring systems where subsurface water conditions exist (API 1979).

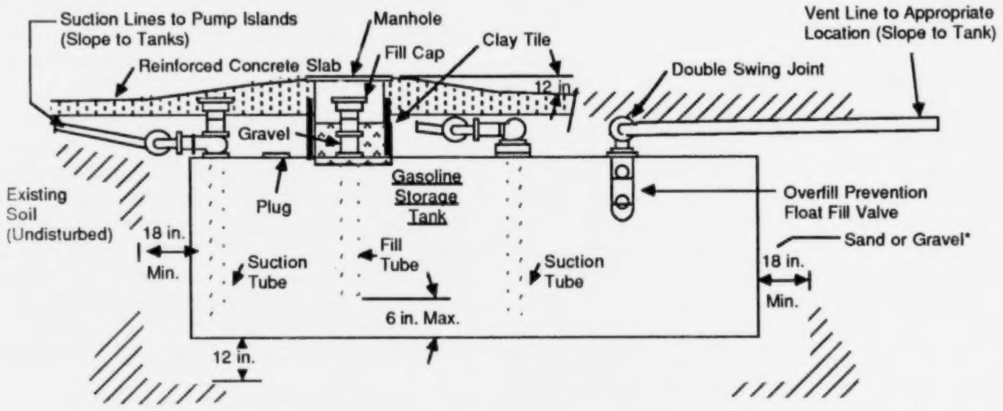


a) Screw or Expandable Type Anchor

b) Concrete Bell (or Deadman) Anchor

c) Concrete Slab Anchor

Figure 2-3. **Components for tank installations with suction pumping (API 1979).**

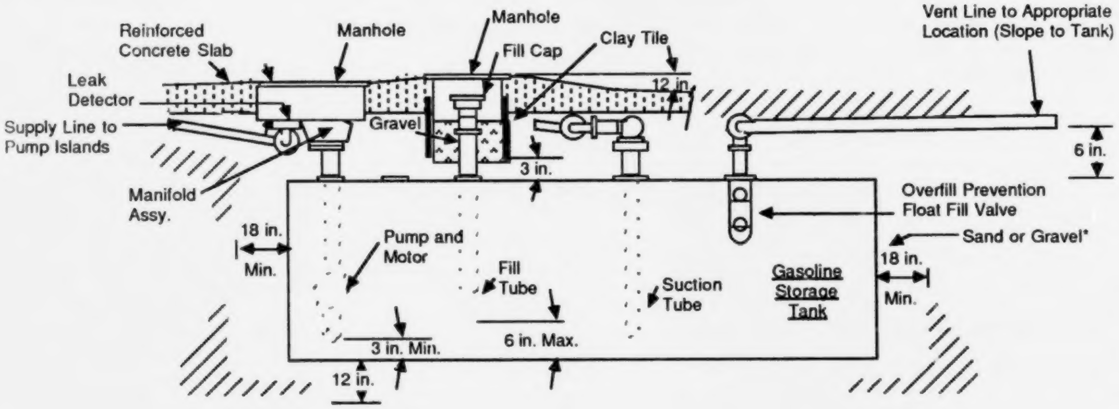

Suction Lines to Pump Islands (Slope to Tanks)
Manhole
Fill Cap
Clay Tile
Vent Line to Appropriate Location (Slope to Tank)
Reinforced Concrete Slab
Double Swing Joint
12 in.
Gravel
Gasoline Storage Tank
Existing Soil (Undisturbed)
Plug
Overfill Prevention Float Fill Valve
18 in.
Min.
Sand or Gravel*
Fill Tube
Suction Tube
Suction Tube
18 in.
Min.
6 in. Max.
12 in.

* PEA Gravel for Nonmetallic Tanks (Or Mfr.-Approved Alternative)

Note: Eliminate concrete slab in nontraffic areas and construct concete (only) around manholes.

Piping Details For Tanks Under Concrete

Figure 2-4. **Components for tank installations with submerged pumping (API 1979).**

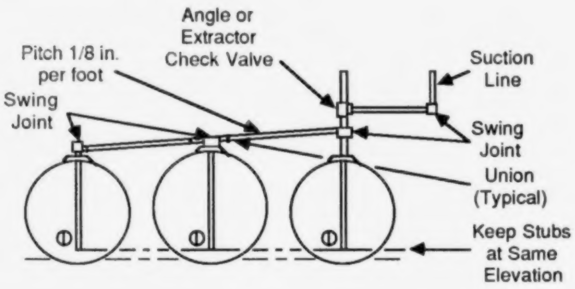

Reinforced Concrete Slab
Manhole
Manhole
Fill Cap
Clay Tile
Vent Line to Appropriate Location (Slope to Tank)
Leak Detector
12 in.
Supply Line to Pump Islands
Gravel
6 in.
3 in.
Manifold Assy.
Overfill Prevention Float Fill Valve
Sand or Gravel*
18 in.
Min.
Pump and Motor
Fill Tube
Suction Tube
Gasoline Storage Tank
18 in.
Min.
3 in. Min.
6 in. Max.
12 in.

* PEA Gravel for Nonmetallic Tanks (or Mfr.-Approved Alternative)

Note: Eliminate concrete slab in nontraffic areas and construct concete (only) around manholes. The extr. angle check riser is not required with earth cover.

Piping Details For Tanks Under Construction

Figure 2-5. **Piping arrangement of external pump (API 1979).**



2.2 Failure Modes

Leaks from underground storage tank systems (i.e., the storage tank and associated piping and pumping) can result from corrosion; from system rupture due to overloading, external stresses, or puncture; and from faulty construction and installation. Overfilling is another potential source of a product release from a tank system.

The most common failure mode of underground tank systems is corrosion of the tank or piping. Corrosion may be traced to failure of the corrosion protection system due to pinholes in the coating or taping system, depletion of the sacrificial anodes, corrosion from the inside due to the stored product, and various other reasons. Many corrosion-related leaks are found in systems that have no corrosion protection at all; these are systems that were installed in the 1960's and 1970's and are now approaching the age when failure is immminent. Tanks having corrosion protection also can corrode, however, if the protective coating is damaged during installation, sacrificial anodes are not replaced when required, the current is switched off in impressed current systems, or the protection system is not designed properly for the soil conditions and stored liquids.

Fiberglass-reinforced plastic (FRP) tanks and piping are inherently corrosion-resistant, but this material of construction has lower structural strength than steel and requires extra care during installation and operation. Reinforced ribs are usually incorporated into their design to withstand both the internal stresses from the stored liquid and the external stresses from backfill. Some resins used for FRP tank construction may lose structural strength when exposed to certain chemicals; others may dissolve, soften, or become brittle in acidic or saline soil environments. Failure to observe the design limitations and to follow the handling and installation requirements for FRP tanks can lead to tank failure and the resultant leaks.

A substantial percentage of leaks in underground storage systems occur in piping systems, probably because the threaded joints used in most of these systems are vulnerable to corrosion from outside if adequate corrosion protection is not provided. Piping joints also may leak because of improper sealing during installation or loosening due to vibration, temperature cycling, and the like. According to practices recommended by the State of New York (no date), the principal causes of pipe failure are as follows:

- Corrosion
- Settlement of backfill
- Frost heave
- Traffic loadings on poorly protected piping
- Stresses resulting from changes in temperature

Overfilling is another source of releases (spills) from tanks. Spills of this type can be caused by human error, failure of the delivery source's shutoff valves, and failure of the tank level indicator. These spills are generally small (less than a few gallons), but they have the potential of becoming much larger if the equipment is left unattended during tank filling or if shutoff valves fail.

The Pennsylvania Department of Environmental Resources (PADER), through investigations of leaking underground storage systems, categorized leaks as 49 percent from tanks, 39 percent from piping, and 12 percent from both tanks and piping (Water Information Center, Inc. 1986). They further report that 53 percent of the piping leaks occurred within 10 years of tank installation and 77 percent within the first 15 years. In contrast, 71 percent of the tank leaks occurred more than 10 years after installation and 46 percent after 15 years. According to PADER, the three major causes of leaks were corrosion (62 percent), loose fittings (19 percent), and improper tank installation (13 percent). They also found a preponderance of systems that had no cathodic protection whatsoever.

Table 2-2. Comparison of Containment Systems for UST Releases[*]

Type of System	Advantages	Disadvantages	Relative Cost
Clay Liners	If available close to the site, clay provides the least expensive liner use of clay is a well-established practice and standard testing procedures are available	Subject to drying and cracking; therefore, must be protected with soil cover; subject to leaching of components when exposed to ground water or other solutions; subject to ion exchange when exosed to water containing acids, alkalis, or dissolved salts; subject to destabilization when exposed to some organic solvents	Low
Polymeric Liners	Provide well-established solution to problem of containing petroleum products; particularly good for temporary storage; high resistance to bacterial deterioration	Require subgrade preparation and sterilization to reduce risk of puncture; must be protected for damage, particularly that due to vehicular traffic; must be protected from sunlight and ozone; may be attached by hydrocarbon solvents, particularly those with high aromatic content; good oil resistance and good low-temperature properties do not normally go hand in hand	Moderate to high
Soil Cement	Is durable; resistant to aging and weathering	Subject to degradation due to frost heaving of subgrade; in-place soil normally used; permeability varies with the type of soil	Moderate
Bentonite	Has low permeability; does not deteriorate with age; is self-sealing	Untreated bentonite may deteriorate when exposed to contaminant; requires protective soil cover, typically 18 inches; subject to destabilization when exposed to some organic solvents	Moderate
Concrete Vaults	Has good strength and is durable	Requires surface coating to ensure impermeability; subject to cracking when exposed to freeze/thaw cycles	High
Double-Walled Tanks	Constructed of material (FRP or coated steel) that is resistant to the stored product and to external corrosion; tank design includes leak-detection system	Some models only available in tank sizes up to 4,000 gal.	High

[*] Data from State of New York, 1983.

Section 3
Leak Detection and Environmental Assessment

This section presents a brief review of techniques for detecting underground tank leaks and methods for making an initial assessment of the extent of the resulting product release to the environment. These techniques are discussed in greater detail in a recent EPA report (Niaki and Broscious 1986). Both early identification of leaks and a prompt assessment of their impact are necessary to minimize the adverse effects of releases from USTs. A continuing tank monitoring program and accurate leak detection systems are essential. In addition, when a release is discovered, accurate characterization of the extent of release and the pathways of migration is critical to planning response actions.

3.1 Tank Monitoring

Methods for detecting leaks in underground storage tanks fall into four general classes:

1) Volumetric (quantitative) leak testing and leak rate measurement
2) Nonvolumetric (qualitative) leak testing
3) Inventory control
4) Monitoring of leak effects

These methods can be used independently or in combination. Efforts are being made by EPA's Hazardous Waste Engineering Research Laboratory to evaluate the relative effectiveness of select technologies within these groups at the Edison, New Jersey,facility by using control tanks.

3.1.1 Leak Test Technologies

3.1.1.1 Volumetric (Quantitative) Leak Testing

This type of testing is based on detecting a change in tank volume by measuring parameters such as liquid level, temperature, pressure, and density. Among the techniques used are an air bubbling system that monitors pressure changes resulting from changes in product level in the tank; a "J" tube manometer that measures pressure changes; and two methods to measure changes in liquid levels: a laser beam and its reflection, and a "dip-stick" type device. Another approach is to measure any volume change by maintaining a constant level. Some volumetric leak testing methods can reportedly detect leak rates as low as 0.02 gal/h (Niaki and Broscious 1986). Table 3-1 presents a summary of information on available volumetric leak detection methods. This listing is not considered exhaustive. Costs listed under "cost of testing" do not necessarily include all testing costs incurred during leak detection.

3.1.1.2 Nonvolumetric (Qualitative) Leak Testing

Testing for leaks by qualitative methods usually involves the use of another material besides the product (tracer material). When the tracer material, typically helium, is used to pressurize a tank, a loss of pressure or the detection of the tracer gas outside the tank by a sniffer mass spectrometer indicates a leak. Helium's rapid diffusivity allows it to escape through a tank leak as small as 0.005 inch (Niaki and Broscious 1986). Other nonvolumetric methods of detecting leaks include pressurizing a tank with gas or placing it under vacuum and using sound detection to listen for a hiss of gas escaping or the bubbling sound of gas entering the tank and rising through the liquid contents. The primary concern with the use of qualitative testing methods is the potential for causing greater leakage, their effect on product quality, the possibility of an explosion hazard, the inability to measure the leak rate and the time required for testing (Niaki and Broscious 1986). This form of testing is best suited for determining the presence of a leak, followed by volumetric testing to determine the rate of leakage. Table 3-2 presents a summary of information on available nonvolumetric leak detection methods. Again, this listing is not considered exhaustive.

3.1.1.3 Inventory Control or Inventory Monitoring

This is perhaps the simplest and most economical leak-detection method. Table 3-3 presents a summary of information on the use of inventory control (and leak effects monitoring). The information presented in this table is not considered exhaustive. Leaks can be detected by keeping records of tank inventories and noting any unexplained change in liquid levels or amounts. Inventory monitoring can be performed by gage stick, electronic level measurement, or by weight

Table 3-1. **Summary of Volumetric Leak Detection Methods***

Method	Principle	Claimed Accuracy (gal/h)	Cost of Testing†	Total Down-Time for Testing	Requires Empty/Full Tank for Test
Inventory monitoring					
Gage stick	Measuring project level with dip stick when station is closed	Gross	Minimal	Variable†	No
MFP-414 TLG leak detector	Monitoring product weight by measuring pressure and density at the top, middle, and bottom of tank	Sensitive to 0.1% of product height change	\$5000 to \$6000 (equipment)	None	No
TLS-150	Using electronic level measurement device or programmed microprocessor inventory system	Sensitive to 0.1-in. level change	\$5000 (equipment)	None	No
Monitoring of leak effects					
Collection sumps	Using collection mechanism of product in collection sump through sloped floor under the storage tank	Does not provide leak rate	Provided by contractor	None	No
Dye method	Hydrocarbon detection by use of soluble dye through perforated pipe	Does not provide leak rate	Provided by contractor	None	No
Ground-water and soil sampling	Water and soil sampling	Does not provide leak rate	Provided by contractor	None	No
Interstitial monitoring in double-walled tanks	Monitoring in interstitial space between the walls of double-walled tanks with vacuum or fluid sensors	Does not provide leak rate	Provided by tank manufacturer	None	No
L.A.S.P.	Diffusion of gas and vapor to a plastic material	Does not provide leak rate	Provided by contractor	None	No

Table 3-1. (Continued)

Method	Principle	Claimed Accuracy (gal/h)	Cost of Testing†	Total Down-Time for Testing	Requires Empty/Full Tank for Test
Mooney tank test detector	Measuring level change with a dip stick	0.02	$250/tank 1- to 2-h test)	14 to 16 h‡(12 to 14 h waiting after fillup,	Full
PACE tank tester	Magnification of pressure change in a sealed tank by using a tube (based on manometer principle)	Less than 0.05	Not commercial	14 h	Full
PALD-2 leak detector	Pressurizing system with nitrogen at three different pressures; level measurement by an electro-optical device; estimate of leak rate based on the size of leak and pressure difference across the leak	Less than 0.05	Not commercial	14 h (preferably 1 day before, 1-h fill testing, includes sealing time)	Full
Pneumatic testing	Pressurizing system with air or other gas; leak rate measurement by change in pressure	Gross	Low	Several hours	No
Tank auditor	Principle of Buoyancy	0.00001 in the fill pipe; 0.03 at the center of a 10.5-ft-diameter tank	$400/tank	1.5 to 3 h	Typically full
Two-tube laser interferometer system	Measuring level change by laser beam and its reflection	Less than 0.05	Not commercial	4 to 5 h§	No (at existing level)

* Data from Niaki and Broscious 1986.

† Charges could be negotiated with manufacturer or different numbers of tank testing and different tank specifications.

‡ Including the time for tank end stabilization with testing with standpipe.

§ Including 1 to 2 h for reference tube temperature equilibrium.

Table 3-2. Summary of Nonvolumetric Leak Detection Methods*

Method	Principle	Claimed Accuracy (gal/h)	Cost of Testing†	Total Down-Time for Testing	Requires Empty/Full Tank for Test
Acoustical Monitoring System (AMS)	Sound detection of vibration and elastic waves generated by a leak in a nitrogen-pressurized system; triangulation techniques to detect leak location.	Does not provide leak rate; detects leaks as low as 0.01 gal/h	Not commercial	1 to 2 h	No
Leybold-Heraeus helium detector, Ultratest M2	Rapid diffusivity of helium; mixing of a tracer gas with products at the bottom of the tank; helium detected by a sniffer mass spectrometer	Does not provide leak rate; helium could leak through 0.005-in. leak size	By contractor	None	No
Smith & Denison helium test	Rapid diffusivity of helium; differential pressure measurement; helium detection outside a tank	Provides the maximum possible leak detection based on the size of the leak (does not provide leak rates); helium could leak through 0.05-in. leak size	By contractor	Few - 24 h (excludes sealing time)	Empty
TRC rapid leak detector for underground tanks and pipes	Rapid diffusion of tracer gas; mixing of a tracer gas with product; tracer gas detected by a sniffer mass spectrometer with a vacuum pump	Does not provide leak rate; tracer gas could leak through 0.005-in. leak size	By contractor	None	No
Ultrasonic leak detector (Ultrasound)	Vacuuming the system (5 psi); scanning entire tank wall by ultrasound device; noting the sound of the leak by headphones and registering it on a meter	Does not provide leak rate; a leak as small as 0.001 gal/h of air could be detected; a leak through 0.005 in. could be detected	Not commercial	Few hours (includes tank preparation and 20-min test)	Empty
VacuTect (Tanknology)	Applying vacuum at higher than product static head; detecting bubbling noise by hydrophone; estimating approximate leak rate by experience	Provides approximate leak rate	$500/tank	1 h	No
Varian leak detector (SPY2000 or 938-41)	Similar to Smith & Denison	Similar to Smith & Denison	Varies by contractor	Few - 24 h (excludes sealing time)	Empty

* Data from Niaki and Broscious 1986.

† Charges could be negotiated with manufacturer for different numbers of tank testing and different tank specifications.

Table 3-3. Summary of Other Leak Detection Methods*

Method	Principle	Claimed Accuracy (gal/h)	Cost of Testing†	Total Down-Time for Testing	Requires Empty/Full Tank for Test
Ainlay tank integrity testing	Pressure measurement by a coil-type manometer to determine product level change in a propane bubbling system	0.02	$225/day + exp. (3 tanks/day)	10 to 12 h (filled a night before 1.5 h testing)	Full
ARCO HTC underground tank detector	Level change measurement by float and light-sensing system	0.05		4 to 6 h	No
Certi-Tec testing	Monitoring of pressure changes resulting from product level changes	0.05		4 to 6 h	Full
"Ethyl" tank sentry	Level change magnification by a "J" tube manometer	Sensitive to 0.02-in. level change	$300/tank	Typically 10 h	No
EZY-CHEK leak detector	Pressure measurement to determine product level change in an air bubbling system	Less than 0.01	$300/tank	4 to 6 h (2 h waiting after fillup, 1-h test)	Full
Fluid-static (standpipe) testing	Pressurizing of system by a standpipe; keeping the level constant by product addition or removal; measuring rate of volume change	Gross	Low	Several days	Full
Heath Petro Tite tank and line testing (Kent-Moore)	Pressurizing of system by a standpipe; keeping the level constant by product addition or removal; measuring volume change; product circulation by pump	Less than 0.05	$75/1000 gal	6 to 8 h	Full
Helium differential pressure testing	Leak detection by differential pressure change in an empty tank; leak rate estimation by Bernoulli's equation	Less than 0.05		Minimum 48 h	Empty

Table 3-3. (Continued)

Method	Principle	Claimed Accuracy (gal/h)	Cost of Testing[†]	Total Down-Time for Testing	Requires Empty/Full Tank for Test
Leak Lokator test hunter–formerly Sunmark Leak Detection	"Principle of Buoyance." The apparent loss in weight of any object submerged in a liquid is equal to the weight of the displaced volume of liquid	0.05 even at product level at the center of a tank	$500/tank	3 to 4 h	Typically full
Observation wells	Product sensing in liquid through monitoring wells at areas with high ground water	Does not provide leak rate	Varies by contractor	None	No
Pollulert and Leak-X	Difference in thermal conductivity of water and hydrocarbon through monitoring wells	Does not provide leak rate	Varies by contractor	None	No
Remote infrared sensing	Determining soil temperature characteristic change due to the presence of hydrocarbons	Does not provide leak rate	Varies by contractor	None	No
Surface geophysical methods	Hydrocarbon detection by ground-penetrating radar, electromagnetic induction, or resistivity techniques	Does not provide leak rate	Varies by contractor	None	No
U-Tubes	Product sensing in liquid; collection sump for product directed through a horizontal pipe installed under a tank	Does not provide leak rate	Varies by contractor	None	No
Vapor wells	Monitoring of vapor through monitoring well	Does not provide leak rate	Varies by contractor	None	No

[*] Data from Niaki and Broscious 1986.

[†] Charges could be negotiated with manufacturer for different numbers of tanks and different tank specifications.

monitoring (i.e., using pressure and density measurements to determine weight changes in tank contents). Although the problem of keeping records of tank inventory is complicated by the fact that petroleum products and other chemicals are volatile and losses due to evaporation are unavoidable, the inventory method can be used as a first and convenient method for gross leak monitoring. A long-term (greater than 4 months) tabulation of inventory records, properly graphed with adjustments for temperature, aids in leak detection.

3.1.1.4 Monitoring of Leaks Effects

Leaks in USTs can be detected by monitoring the environmental effects of a leak inside or outside the tank. This type of monitoring typically entails drilling monitoring wells, installing monitoring casings, and performing chemical analyses. With environmental-effects monitoring, it may be difficult to determine which tank is leaking when there is more than one tank; however, leak detection may be more conclusive than quantitative testing methods if no interfering substances are present. These methods do not provide information on leakage rates or the size of the leak; however, once installed, a leak effects monitoring system enables more frequent checking to be made for leaking tanks than do the other approaches.

3.1.2 Leak Detection Variables

How accurately leak-detection methods pinpoint leaks and measure rates of leakage depends on several variables as well as the method itself. Table 3-4 lists the major variables that affect the accuracy of currently available leak-detection methods.

During tank testing, most of these variables can be compensated for by such techniques as measuring temperatures and pressures in the tank and considering measured variations in the pertinent calcu-

Table 3-4. Variables Affecting Accuracy of Leak Detection*

Variable	Impact
Temperature change	Expansion or contraction of a tank and its contents can mask leak and/or leak rate.
Water table	Hydrostatic head and surface tension forces caused by ground water may mask tank leaks partially or completely.
Tank deformation	Changes or distortions of the tank due to changes in pressure or temperature can cause an apparent volume change when none exists.
Vapor pockets	Vapor pockets formed when the tank must be overfilled for testing can be released during a test or expand or contract from temperature and pressure changes and cause an apparent change in volume.
Product evaporation	Product evaporation can cause a decrease in volume that must be accounted for during a test.
Piping leaks	Leaks in piping can cause misleading results during a tank test because many test methods cannot differentiate between piping leaks and tank leaks.
Tank geometry	Differences between the actual tank specifications and nominal manufacturer's specification can affect the accuracy of change in liquid volume calculations.
Wind	When fill pipes or vents are left open, wind can cause an irregular fluctuation of pressure on the surface of the liquid and/or a wave on the liquid-free surface that may affect test results.
Vibration	Vibration can cause waves on the free surface of the liquid that can cause inaccurate test results.
Noise	Some nonvolumetric test methods are sound-sensitive, and sound vibrations can cause waves to affect volumetric test results.
Equipment accuracy	Equipment accuracy can change with the environment (e.g., temperature and pressure).
Operator error	The more complicated a test method, the greater the chance for operator error, such as not adequately sealing the tanks if required by the test method in use.
Type of liquid stored	The physical properties of the liquid (including effects of possible contaminants) can affect the applicability or repeatability of a detection method (e.g., viscosity can affect the sound characteristics of leaks in acoustical leak detection methods).
Power vibration	Power vibration can affect instrument readings.
Instrumentation limitation	Instruments must be operated within their design range or accuracy will decrease.
Atmospheric pressure	A change in this parameter has the greatest effect when vapor pockets are in the tank, particularly for leak-rate determination.
Tank inclination	The volume change per unit of level change is different in an inclined tank than in a level one.

* Data from Niaki and Broscious 1986.

lations, thorough training of operators to minimize operator errors, inspection for any noticeable vapor pockets, care in sealing vents and fill pipes where applicable, and thorough calibration of instruments and other equipment. (More detailed discussions of these techniques are presented in Subsections 3.3 and 4.2.)

3.2 Contaminant Migration (Transport) Pathways

An understanding of how contaminants released from underground tanks migrate in the subsurface environment is critical to evaluating the impact of any release. The migration, or transport, of these releases depends primarily on the quantity released, the physical properties of the substance, and the structure of the soils and rock through which the contaminant moves. Figure 3-1 shows the typical subsurface environment of USTs.

3.2.1 Unsaturated Zone (Vadose Zone)

When a liquid contaminant is released below the ground surface, it percolates downward to the unconfined ground-water surface. In the case of a small-quantity release, the contaminant may be held in the interstices of the soil particles in this zone and may not reach the saturated zone except as it is slowly displaced and carried downward by percolating rainwater. In the case of large releases, however, movement through this zone may be quite rapid.

If surface soils were homogenous and isotropic, the only lateral movement of percolating product would be from capillarity effects, and the resultant contaminant-soaked soil would be an inverted narrow cone. Because typical spill sites are nonhomogenous, the resultant product spread through the unsaturated zone is usually irregularly shaped (Figure 3-2).

If the soil and product properties are known, whether the product will reach the ground water can be estimated. The following formula provides a useful approximation for hydrocarbons:

$$D = \frac{Rv\,V}{A}$$

where

D = maximum depth of penetration, m

V = volume of infiltrating hydrocarbon, m^3

A = area of spill, m^2

Rv = a constant reflecting the retention capacity of the soil and the viscosity of the product (see Table 3-5).

Figure 3-1. Diagram of typical subsurface environment of USTs (Camp, Dresser, and McKee 1986a).

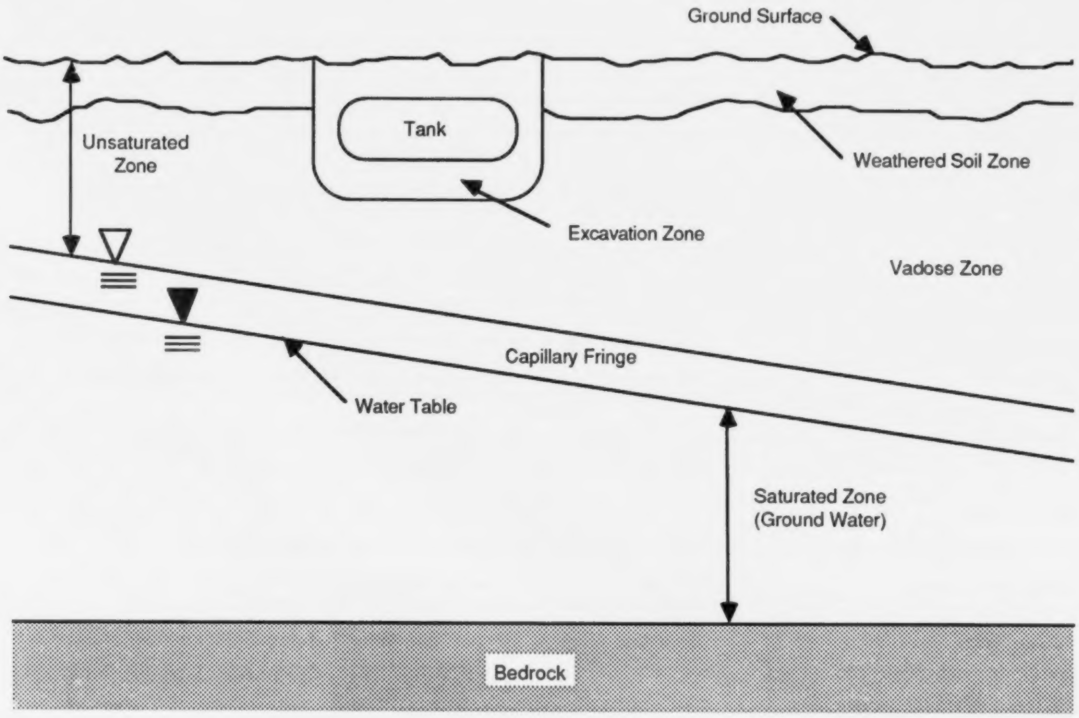


Figure 3-2. **Shape of hydrocarbon plume in vadose zone under different leakage rates and physical conditions (API 1985).**

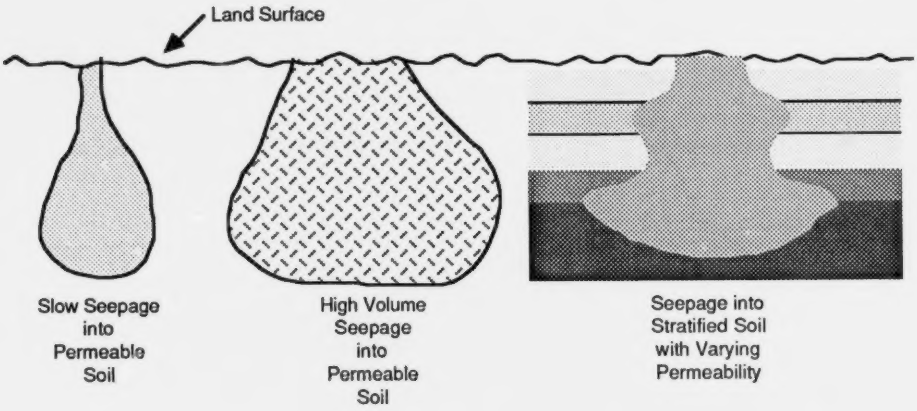

Land Surface
Slow Seepage into Permeable Soil
High Volume Seepage into Permeable Soil
Seepage into Stratified Soil with Varying Permeability

Table 3-5. **Typical Values for Rv**[*]

Soil	Rv†		
	Gasoline	Kerosine	Light Fuel Oil
Coarse Gravel	400	200	100
Gravel to Coarse Sand	250	125	62
Coarse to Medium Sand	130	66	33
Medium to Fine Sand	80	40	20
Fine Sand to Silt	50	25	12

[*] Data from Shepherd, no date.

† A constant value representing capacity of soil and viscosity of product.

The usefulness of the calculations is limited by the accuracy of the Rv values, which are extremely site-specific. The Rv values given in Table 3-5 are estimates for dry soil conditions. Obviously, values for wet or partially wet soils would be less because pore voids are already partially filled. Retention (attenuative) capacities for hydrocarbons vary from about 5 liters/m³ in coarse gravel to more than 40 liters/m³ in silts. A leaked substance such as gasoline can travel 25 feet through unsaturated, permeable, alluvial, or glacial sediments in a few hours (or at most, a few days) depending on specific conditions at the release site.

3.2.2 Capillary Zone

The capillary zone has a significant impact on the movement of nonaqueous-phase liquids that are less dense than water (gasoline and other petroleum products). Figure 3-3 presents a typical flow pattern for hydrocarbons in the capillary zone.

The primary movement in the capillary zone is lateral. As more free oil reaches the capillary fringe, a layer of increasing thickness (a lens) begins to form on the capillary fringe under the influence of the infiltrating oil. The weight of the oil may result in the depression of the capillary fringe and possibly the water table (Figure 3-4).

Buoyant forces act to restore the water to its initial level, and if a critical minimum thickness (which varies with soil and contaminant properties) is exceeded, lateral spreading begins. Lateral spreading will occur in all directions, but the predominant movement will be with the slope of the water table (Figure 3-5).

The characteristic shape of the flow is called an "oil pancake." The shape of the pancake depends on the permeability of the soil, the percolation rate, and the local water-table configuration. In general, the more permeable the soil, the more the contaminant will spread and the less thick the recharge lens will be. The steeper the hydraulic gradient, the narrower the plume will be and it will be elongated in the direction of ground-water flow.

As the water table fluctuates over time, the nonaqueous-phase liquid contaminant may spread out somewhat in the vertical plane. In porous media, this can lead to an apparent decrease in the volume of free product, as previously uncontaminated soil will now retain (adsorb) some of the contaminant. In fractured rock media, on the other hand, an apparent increase in the volume of free product may occur as contaminants trapped in dead-end fractures not previously unconnected with the water table may be washed out.

Figure 3-3. **Typical flow pattern for hydrocarbons in the capillary zone (Shepherd, undated).**

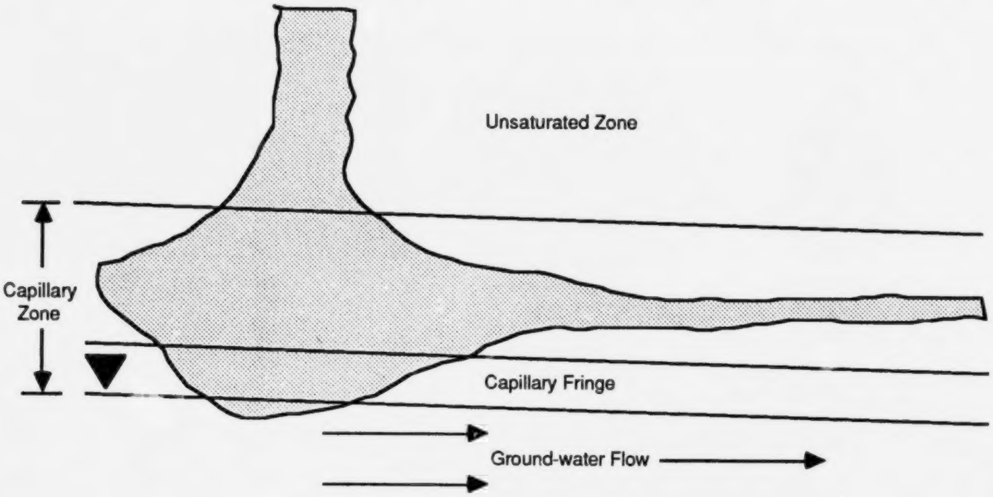

Unsaturated Zone
Capillary Zone
Capillary Fringe
Ground-water Flow

Figure 3-4. **Typical behavior of hydrocarbons in soil following a sudden high-volume release (API 1980).**

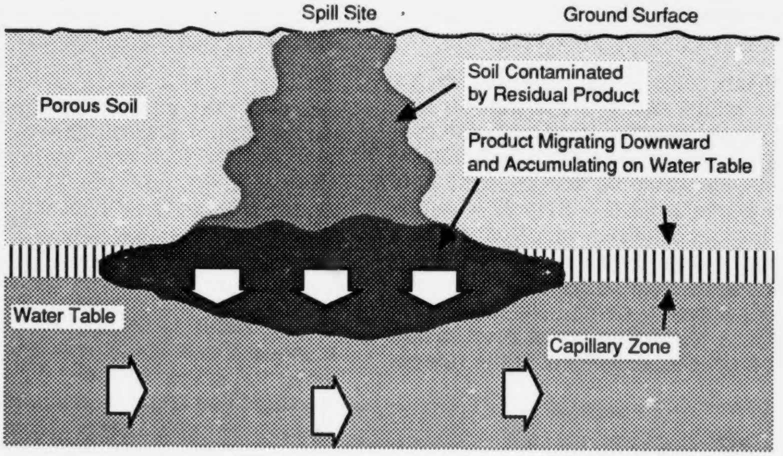
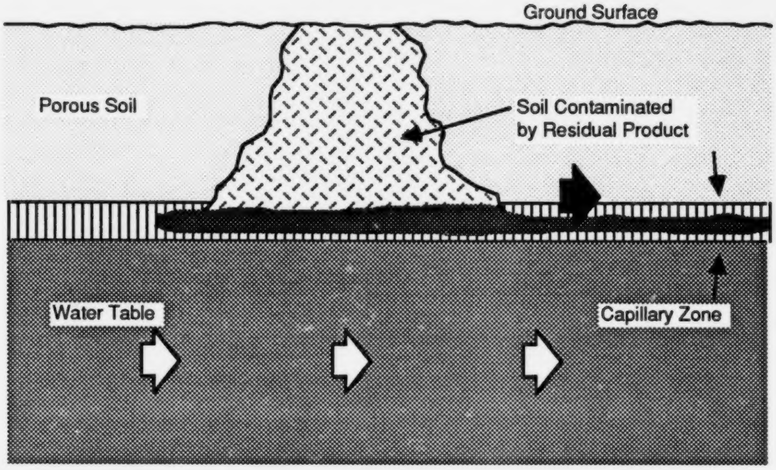

Spill Site
Ground Surface
Porous Soil
Soil Contaminated by Residual Product
Product Migrating Downward and Accumulating on Water Table
Water Table
Capillary Zone

Figure 3-5. **Behavior of hydrocarbons after release has stabilized (API 1980).**



3.2.3 Saturated Zone

The transport of contaminants in the saturated zone can be characterized for three classes of substances:

1) Miscible or dissolved substances
2) Immiscible substances with specific gravity of less than 1.0
3) Immiscible substances with specific gravity of more than 1.0.

According to the mass transport laws of advection and dispersion, miscible substances that enter the ground water move in the general direction of ground-water flow. Advection is the movement of a contaminant plume with the mean ground-water flow. Dispersion refers to the spreading out and dilution of a contaminant as it occupies more of the saturated zone than can be explained only by advection. The three levels of dispersion are molecular diffusion, microscopic dispersion, and macroscopic dispersion. Macroscopic dispersion, which is due to variations in soil permeability (heterogeneity), is the principal phenomenon in most field situations.

Immiscible substances that are "lighter" than water (a specific gravity of less than 1.0) are usually found only in the shallow part of the saturated zone. The rate of transport probably depends on the local ground-water gradients and the viscosity of the substance.

Immiscible substances that are denser than water (specific gravity greater than 1.0) move downward through the saturated zone. A dense immiscible substance poses a greater danger in terms of migration potential than less dense substances because their deeper penetration into the saturated zone increases the potential for its solution and dissolved components then migrating with the prevailing ground-water flow pattern. Although some residual saturation (and therefore retention in the soil) occurs as the substance moves downward, it is less than in the unsaturated zone. If the quantity of release exceeds the retention capacity of the unsaturated and saturated zones, the nonaqueous-phase liquid continues its downward migration until it reaches an impermeable boundary. At this point it forms a lens and spreads with the slope of the barrier and pools in depressions in the boundary.

3.2.4 Vapor Phase Transport

A liquid contaminant leaking from an underground tank enters the vapor phase in the unsaturated zone according to its specific vapor pressure (the higher the vapor pressure of the substance, the more likely it is to evaporate). Once in the vapor phase, the contaminant moves by advection and by diffusion. Vapors move primarily in a horizontal direction, controlled by the slope of the water table and the location of "impermeable" barriers. Those vapors less dense than air, however, often migrate in a vertical direction, which results in their entrainment in sewer lines, basements, and like areas.

Molecules of gas may adhere to soil particles by adsorption and then be released at a later time after passage of the plume of fluid contamination. Vapor movement can be blocked by monolithic buried structures, but the vapors will move readily through the backfill surrounding such structures (such as along the route of a buried pipeline).

3.3 Initial Assessment of Extent of Release

When a leak is discovered or suspected, an initial assessment must be made of the risk posed to human health and the environment must be made quickly. This assessment should provide an approximation of the extent (lateral and vertical dimensions) and severity (quantification of specific constituents present) of the contamination problem. The assessment results will be used to design and implement programs for rapid control of the spread of contaminants (if necessary), or to define additional data collection programs before remedial action programs are developed.

The initial assessment may consist of one or both of the following: 1) data collection from existing sampling points, and 2) installation of new sampling points for data collection.

3.3.1 Existing Sampling Points

Existing sampling points include inventory records, underground structures, water-supply wells, and surface water bodies. Frequently, existing sampling points can provide a good estimate of health and environmental effects of a leak. Some provide a place of environmental contact (e.g., a water-sampling well). Identification of contaminants in receptors usually is sufficient to prompt emergency response actions.

3.3.1.1 Inventory Records

Inventory records are frequently the trigger mechanism to indicate that a leak has occurred. They also can indicate the approximate quantity of material released by a leak. Such records are especially useful where both inflow and outflow are monitored (such as in retail gasoline facilities). Pinpointing the amount of loss may be difficult, however, because of inaccuracies in the gaging and metering devices used to measure fluid movement into and out of the tank.

3.3.1.2 Underground Structures

Sizable releases of volatile substances, including gasoline, may be associated with gas migration and releases of toxic or volatile vapors at or near the ground surface. Basements and sewers, for example, may accumulate vapors migrating through the soil from underground tank releases, and such vapors sometimes reach explosive concentrations. Monitoring in such underground areas can identify symptoms of tank leakage.

Several kinds of currently available air monitoring instruments can locate and quantify vapor releases to confined underground spaces. Explosimeters and oxygen meters can determine the existence of an explosive atmosphere. These instruments report volatile vapor concentrations as a percentage of the lower explosive limit (LEL). The oxygen meters that are normally included in the explosimeter instrument can identify high concentrations of vapors by indicating the displacement of oxygen by some other gas.

Among a variety of more sensitive direct-reading instruments currently on the market for detecting and quantifying vapors are the organic vapor analyzer (OVA) and the PI 101 Hazardous Waste detector.

The Century OVA, a lightweight shoulder-borne instrument manufactured by the Foxboro Corporation, can monitor volatile organic compounds in the air through the use of a flame ionization detector (FID). This instrument can be assembled as a total organic "sniffer" or as a portable gas chromatograph (GC), which can also function as a sniffer.

When used as a sniffer, a hand-held output meter attached to a sample probe collects the air and indicates the concentration of nonmethane compounds in the air sample in parts per million. When the OVA is assembled as a portable GC, a sample is introduced into the GC column for quantitative determination of its components. A strip chart recorder provides a printout of the response in peaks similar to those obtained with a laboratory-scale GC.

The Model PI 101 Hazardous Waste Detector, a portable gas analyzer manufactured by HNU Systems, Inc., was designed to detect the presence of potentially harmful chemical vapors. It operates on the principle of photoionization and is sensitive to a wide range of both organic and inorganic compounds.

Model PI 101 uses different sample probes equipped with a lamp of different energy levels (9.5 eV, 10.2 eV, 11.7 eV). Positive identification of suspect compounds is based on correlation of the known ionization potential of the suspect compound with that of the appropriate probe. A direct-concentration readout provides results in parts per million.

Sorbent tubes can provide both qualitative and quantitative information. A known volume of air is pumped through the sorbent tube, and the contaminants in this sample are adsorbed and concentrated on the sorbent material in the sampling tube. Some sorbent tubes can be taken into the laboratory for treatment and analysis to determine concentrations of a variety of constituents. Others are designed to register the presence of only a single compound or group of compounds based on a colorimetric change produced as the sample is drawn through the tube.

3.3.1.3 Water Supply Wells

One of the most serious threats posed by releases from USTs is the contamination of residential and municipal drinking water wells. Such wells should be sampled promptly when a leak is known to have occurred. The locations of wells in a particular vicinity can be obtained from several sources, including city or county engineers, local water companies, local health departments, and direct communication with nearby residents.

Whenever possible, well-water samples should be analyzed in a laboratory, particularly when the exact nature of the contamination has not been confirmed; however, several usable screening techniques and test kits are available for field analysis of water samples. Table 3-6 presents a partial listing of portable field instruments for water monitoring.

3.3.1.4 Surface Water Bodies

Nearby surface water bodies, including enclosed sewers and drains, should be sampled as they reflect points of potential release from the subsurface environment. Like well-water samples, analysis should be done in a laboratory, but field identification may be necessary to expedite initiation of a surface-water management program.

3.3.2 New Sampling Points

When no existing sampling points can provide qualification of the risk posed by a leak or these sampling points fail to show any effects, new sampling points must be developed to define the problem.

Both direct and indirect methods are available to collect data from these new sampling points. Indirect methods generally comprise remote sensing techniques, whereas direct methods involve extraction of soil and liquid samples for direct chemical analysis.

3.3.2.1 Indirect Methods

As defined herein, indirect methods include geophysical surveys and soil vapor analysis.

Several geophysical survey techniques are available to define subsurface water quality conditions. The two most frequently used are electrical resistivity and electromagnetic conductivity. Both methods work best for leakage of inorganic fluids with high ionic strength, but they may be used for some organics with high isolating capabilities.

Use of the resistivity survey requires the introduction of a known electrical current into the ground with electrodes. The amperage of the current is measured at other electrodes, and the resultant decrease (resistance of the earth) is also measured. If geologic conditions are uniform, high earth resistance indicates general absence of ionic contaminants and low resistance indicates the presence of ionic contaminants. The procedure can be used to measure both vertical and lateral changes. The presence of metallic objects (pipes, tanks, etc.) or electrical sources (power lines) can interfere with the procedure.

Essentially a corollary to the resistivity survey, the electromagnetic conductivity (EM) survey has similar limitations and interferences. The EM survey is usually quicker, but it provides only limited vertical evaluation.

Recently, developed procedures for direct measurement of vapors in soils involve the use of the following instruments: surface flux chambers, downhole flux chambers, accumulator devices, and ground probes.

Surface Flux Chambers

The surface flux chamber is an enclosed device used to sample the gaseous emissions from a defined area on the ground surface. Clean, dry, sweep air is added to the chamber at a controlled and measured rate, and the concentration of the species of interest is measured at the exit of the chamber. Analysis is by portable gas analyzer or GC.

Downhole Flux Chambers

The downhole flux chamber operates on the same principle as the surface flux chamber. It is either driven into the ground or placed down an augered hole. Sweep air is added, and the exit gas concentration is monitored. Analysis is by portable gas analyzer or GC. The downhole flux chamber is more sensitive than the surface flux chamber because sampling occurs at depths below any surface interferents and where soil gas concentrations are normally at higher levels.

Accumulator Devices

Use of the accumulator devices involves collecting and concentrating soil gases to provide a time-integrated sample. One variation is to collect gases on activated charcoal bonded to a curie-point wire. Analysis is by mass spectrometry. A second variation is to pump gases from an enclosure or ground probe and then collect the gas in an absorbent. The primary advantage of this technique is that the sampling time can be adjusted to reach the desired sensitivity.

Ground Probes

The use of ground probes involves placing a tube into the ground to the desired sampling depth. Openings in the tube near the leading edge allow the entry of soil gases. A port in the upper end of the tube allows sample gas to be extracted. Analysis is typically by GC. The technique is relatively sensitive, and sampling depth can be varied to reach below interferents or low-concentration areas.

Table 3-6. Water Monitoring Techniques*

Instrument/Manufacturer	Capability/Equipment	Comment
Spectronix Mini-20 Bausch and Lombe, Rochester, NY	Spectrophotometer with wavelength range of 400-800 nm	Battery-operated, compact, easy to operate
Mini Conductivity Meter Hach Chemical Co., Loveland, CO	Three ranges: 0-100, 0-1000, 0-10,000 μmhos	0.7 kg, includes batteries and carrying case
Model 16300 Conductivity Meter Hach Chemical Co., Loveland, CO	± 1% accuracy. Five ranges: 0-2, 0-20, 0-200, 0-2000, 0-20,000 μmhos	3.9 kg, includes battery pack, ac
Model DR/1 Portable Colorimeter Hach Chemical Co., Loveland, CO	pH; 50 different water and wastewater tests	Batteries, AC
Model DR-EL/4 Portable Laboratory Hach Chemical Co., Loveland, CO	Spectrophotometer, titrator, cartridges	
Model CYN-2 Cyanide Test Kit Hach Chemical Co., Loveland, CO	Detection of 0 to 2.6 ppm free cyanide	Colorimetric test
Hazardous Materials Detector Kit Hach Chemical Co., Loveland, CO	Measures pH and detects heavy metals, benzene, phenol, cyanide, conductivity, turbidity, nitrate, nitrogen, color, sulphate, phosphate, NH_3, fluoride	Qualitative tests of nonspecific nature to analyze for classes of compounds
Mark IV Quality/Microprocessor Martex Instruments, Irvine, CA	Measures temperature, salinity, conductivity, depth, pH, specific ions	
Water Analysis Laboratory LaMotte Chemical, Chestertown, MD	Analyzes for alkalinity, NH_3, Cl, Br, I, chromium, copper, Iron, F, nitrate, nitrite, phosphate (low), silica, sulphate, sulphide, pH, turbidity, TDS, conductivity, CO_2, chlorine/salinity, DO	
Luminescence Photometer Analytical Luminescence Lab, Inc., San Diego, CA	Analyzes for bacterial biomass in sludge, toxic levels of waste, saltwater constituents	1.1 kg, maximum of 100 samples/h
8500 DO/BOD Meter L G Mester Co., Millville, NJ	LCD readout in the range of 0 to 20 ppm for use in wastewater, BOD, environmental monitoring applications	
Custom Made Multi-Parameter Test Kit for Water LaMotte Chemical, Chestertown, MD	Tests for amine, CO_2, cyanide, formaldehyde, heavy metals, iodine, Fe, Pb, phenol	Kits are custom made to buyers' specifications
Cas-4 Midwest Research Institute, Kansas City, MO	Monitors the levels of organophosphate and carbonate pesticides in water	12V DC maximum for 8 continuous hours, 110 AC, 13.6 kg

---

* Data from Montgomery, Remeta, and Gruenfeld 1985.

3.3.2.2 Direct Methods

Another method of approximating the extent of both liquid and vapor contaminant migration below the ground surface entails soil borings. The most common application of soil borings involves collection of undisturbed soil core with an auger or drilling a sampling tube into the ground. The collected sample is sealed in a container with minimal head space and sent to the laboratory for analysis.

An effective field screening technique for grab samples of soil cores involves the use of the portable OVA (described earlier). Example soil and/or water from the boring is placed in a septum vial so that it is approximately 3/4 full. The sample is then heated, usually by placing the vial in hot tap water. Air is extracted from the headspace in the vial for evaluation by an OVA, either the sniffer type or the GC type. A comparison of the GC output for the sample with that of a blank, or uncontaminated, soil, can identify areas of major contamination, lesser contamination, and uncontaminated soil.

Section 4
Corrective Action Response Process

This section presents procedures and information for the selection of appropriate initial responses and long-term corrective actions when a leak occurs in an UST. Specific technologies mentioned herein are discussed in detail in Section 5.

The responses to releases from USTs depend on several different factors, largely site-specific. Each incident is unique. The intent of this section, therefore, is to aid the reader in the development of an appropriate corrective-action response when such a release occurs.

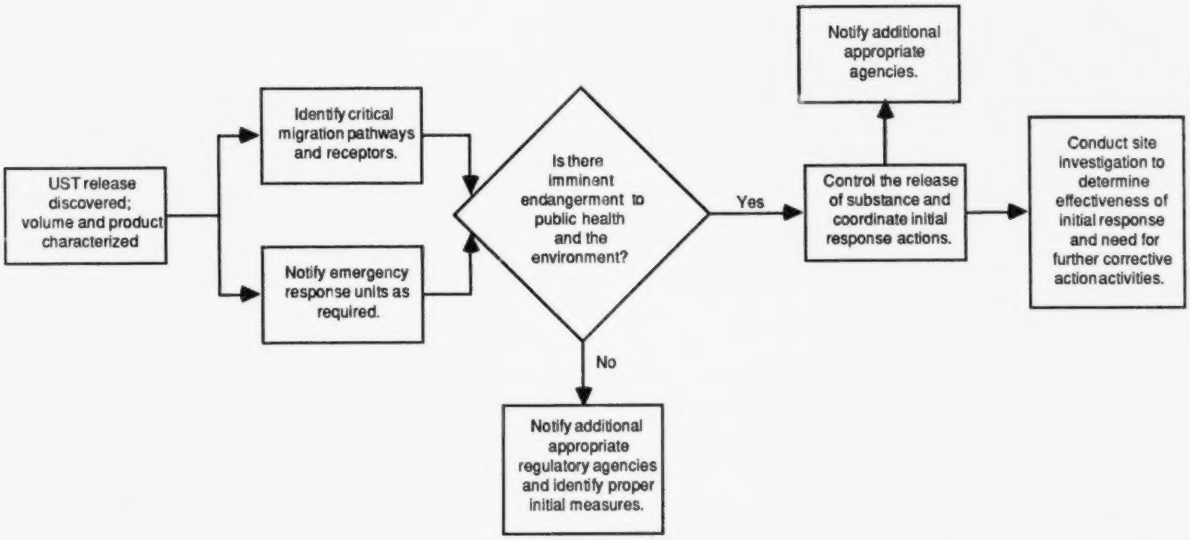
Corrective action usually involves two phases. The first involves the initial corrective actions intended to limit the impact of a sudden or newly discovered release. The second involves long-term, permanent corrective measures. Initial corrective actions (or responses) are those directed at immediately containing and controlling a release. Timing is critical. Therefore, efforts are focused on source control and public welfare. This includes the collection and containment of released material. Permanent corrective measures, on the other hand, involve comprehensive cleanup to protect human health and the environment. Both require an assessment of the situation, which includes the physical and chemical nature of the released substance, the environmental setting of the incident, and the extent of the impact.

The options available for addressing both initial and long-term corrective actions are discussed under the appropriate heading.

4.1 Initial Corrective-Action Options

When a leak in an UST is discovered or occurs suddenly, the initial corrective actions are directed toward collection and containment of the substance released. Initial efforts typically occur within a short time frame, are of brief duration, and involve limited resources. This often entails deployment of field personnel and equipment to the scene within hours of the occurrence to minimize the impact of the release. Figure 4-1 presents typical steps in the decision-making process for selection of initial corrective actions.

Figure 4-1. Typical initial corrective-action process.


UST release discovered; volume and product characterized
Identify critical migration pathways and receptors.
Notify emergency response units as required.
Is there imminent endangerment to public health and the environment?
Yes
No
Control the release of substance and coordinate initial response actions.
Notify additional appropriate agencies.
Conduct site investigation to determine effectiveness of initial response and need for further corrective action activities.
Notify additional appropriate regulatory agencies and identify proper initial measures.

4.1.1 Evaluation of Release

The first step in responding to an UST release usually involves an evaluation of the situation. Such an evaluation entails determining the substance released, the migration pathways and receptors, and the potential impact on human health and the environment. Several offices and field environmental investigative techniques used to evaluate UST releases were discussed in Section 3; this information is not repeated here. This section focuses on incorporating environmental investigative techniques into the response process and identifying significant data requirements for the planning and implementation of response options.

4.1.1.1 Determination of Substance Released

Underground storage tanks are used to store petroleum substances and selected hazardous chemicals. Table 4-1, adapted from a table in a study conducted by Camp, Dresser, and McKee (1986), lists the various petroleum products stored in USTs. Table 4-2, from the same study, lists chemicals stored in USTs.

4.1.1.2 Site Characterization

An important step prior to initiation of a response action is site characterization. How detailed the characterization should be depends on the extent of the release problem and the amount of data required for the planning and implementation of an adequate response action. Figure 4-2 presents a matrix of the corrective action technologies addressed in this report and the typical site information necessary to select, plan, and use a particular technology. The amount of information and data collected during site characterization efforts is related to the complexity of the situation and of the selected corrective action response plan.

A site evaluation should cover hydrogeologic characteristics, geographic and topographic characteristics, and water- and land-use patterns.

Hydrogeologic Characteristics

A hydrogeologic characterization addresses both unsaturated (soils) and saturated (unconsolidated and consolidated) flow and contaminant transport conditions. It involves collection of information concerning the subsurface where the problem exists. Some of this information can be obtained from standardized regional and local reference sources; however, most of the needed data is site-specific and must be obtained by collecting soil, rock, water, and con-

Table 4-1. Petroleum Products Stored in Underground Storage Tanks[*]

Product
Power fuels - civil use
Aviation gasoline and additives
Grade 80
Grade 100
Grade 100LL (low lead)
Jet fuel and additives
Jet A (kerosene type)
Jet A-1 (kerosene type)
Jet B (wide cut or naphtha)
Automotive (motor gasoline) and additives
Leaded
Unleaded
Diesel fuel oil and additives, Nos. 1-D, 2-D, and 4-D
Gas turbine fuel oils, Nos. 0-GT, 1-GT, 2-GT, 3-GT, and 4-GT
Heating and illuminating oils
Fuel oils Nos. 1, 2, 4, 5, and 6
Kerosene
Solvents
Petroleum spirits, types 2, 3, and 4, and commercial hexane
Mineral spirits or Stoddard solvent (Type 1, petroleum spirit)
High-flash aromatic naphthas, types I and II
VM&P naphthas - moderately volatile hydrocarbon solvents, types, I, II, and III
Petroleum extender oils, types 101, 102, 103, and 104

[*] Data from Camp, Dresser, and McKee 1986.

Table 4-2. Selected Chemicals (462) Stored in Underground Storage Tanks*

Acetaldehyde
Actamide,N-9H-fluoren-2-yl
Acetamide,N-(4-ethoxyphenyl)-
Acetone
Acetonitrile
Acetyl chloride
Acrolein
Acrylonitrile
Allyl alcohol
Allylbenzene, 1.2-Methylenedioxy-4-
Amitrole
Aniline
Arodors
Arsenic pentoxide
Benzanthracene,1,2-
Benzenediol,1,3-
Benzofluoranthene,2,3-
Benzoquinone,p-
Benzo[a]pyrene
Bromomethane
Butyl alcohol,-n
Butyl phthalate,n-
Carbamide, N-ethyl-N-nitroso-
Carbamide,N-Methyl-N-nitroso-
Carbon bisulfide
Chlorobenzenamine,4-
Chlorobenzilate
Chloroethene
Chloroethoxyethene,2-
Chloromethane
Chloromethylbenzene
Chloronaphthalene,beta-
Chlorophenol,o-
Chrysene
Cresylic acid
Cresylic acid, o-
Cresylic acid, p-
Crotonaldehyde
Cyanogen chloride
D Acid,2,4-
Dalapon
DDD, 4,4 DDD, TDE
DDE
DDT
Diazoacetate (ester) L-Serine
Dibenzanthracene,1,2:5,6-
Dibenzene Chloride
Dibenzopyrene,1,2:7,8-
Dibromoethane,1,2-
Dibromomethane
Dichlorobenzene,1,2-
Dichlorobenzene,1,3-
Dichloroethyl ether
Dichloromethane
Dicofol
Diepoxybutane,1,2:3,4-
Diethylhydrazine,1,2-
Diisocyanatomethylbenzene,2,4-
Dimethyl ester sulfuric acid
Dimethylbenzene
Dimethylbenzene,m-
Dimethylbenzene,o-
Dimethylbenzene,p-
Dimethylnitrosamine
Dinitrobenzene,1-Methyl-2,4-
Dinitrobenzene,1-Methyl-2,6-
Dioxane,1,4-
Dioxide, 1,3-oxathiolane,2,2-
Epichlorohydrin
Ethanamine,N-Ethyl-N-nitroso-
Ethanol,2,2'-(nitrosamino)bis
Ethanone, 1 phenyl
Ethanoyl bromide
Ethene,trans-1,2 dichloro
Ethyl chloride
Ethyl ester acetic acid
Ethyl ester carbamic acid
Ethyl ester methanesulfonic acid
Ethylene dichloride
Ethylenediamine tetraacetic acid
Ethylenethiourea
Ethylenimine
Ethylidene dichloride
Fluoranthene
Fluoroacetamide,2-
Formic acid 90%
Furfural
Furfuran
Gamma-BHC
Hexachloroethane,1,1,1,2,2,2-
Hexahydrobenzene
Hydrazine
Hydrogen chloride
Hydrogen cyanide
Hydrogen fluoride
Hydrosulfuric acid
Hydroxybenzene
Hydroxydimethylarsine oxide
Iodomethane
Iron dextran
Maleic anhydride
Mercury,(Aceto-o)phenyl-
Methanamine,N-Methyl
Methanol
Methyl ester isocyanic acid
Methyl ethyl ketone
Methyl ethyl ketone peroxide
Methyl isobutyl ketone
Methylamine
Methylbenzene
Methylene oxide
Methylethylbenzene,1-
Methylmercaptan
Methylphenol,2,4-Dinitro-6-
Methylpropanenitrile,2-hydroxy-2-
Methylpropane,1-Amino-2-
Naphthalamine,alpha-
Naphthylamine,2-
Nitrobenzenamine,4-
Nitrogen (II) oxide
Nitrogen (IV) oxide
Nitrogen (VI) oxide
Nitrophenol,4-
Nitrophenol,2-
Nitrosoethenamine,N-Methyl-N-
Nitrosopyridine, Hexahydro-N-
Nitrosopyrrole,Tetrahydro-N-
Octachlorocamphene
Osmium tetroxide
Oxirane
Oxybisethane,1,1-
Oxybis(2-chloropropane),2,2-
Oxybis(chloromethane)
Pb
Pentadiene,1,3-
Phenylazobenzenamine,N-N-dimethy
Phosgene
Phosphine
Phosphorus pentasulfide
Phosphoryl chloride
Phthalate, Di-sec-octyl
Propanal,2,3-Epoxy-1-
Propanamine,1-
Propanamine,n-propyl-1-
Propanenitrile,3-chloro
Propane,2-nitro
Propanoic acid, ethyl ester 2-
Propanol,2-Methyl-1-
Propargyl alcohol
Propenamide,2-
Propenenitrile,2-Methyl-2-
Propenoic acid,2-
Propenoic acid,2-Methylethylethe
Propylamine,N-Nitrosodi-n-
Propylbenzene,1,2-Methylenedioxy
Propylene dichloride
Propylenimine,1,2-
Pyrene,1,10-(1,2-Phenylene)
Pyridinamine,4-
Pyridine,2-methyl
Pyrrolidone,1-Methyl-2-(3-)pyridyl)
Silvex or 2,4,5-TP acid
T acid,2,4,5-
TCDD
Tetrachloroethene,1,1,2,2-
Tetrachloromethane
Tetraethyl ester pyrophosphoric acid
Tetraethl plumbane
Thioacetamide
Thiocarbamide
Thiophenol
Thiram
Toluenediamine
Tribromomethane
Trichloroethane,1,1,1-
Trichloroethene
Trichlorofluoromethane
Trichloromethane
Trimethyl Cyclohexenone
Trinitrate-1,2,3-Propanetriol
Vanadium pentoxide
Vinylidene chloride
(1,1-Biphenyl)-4,4-diamine

---

* Data from Camp, Dresser, and McKee 1986a.

Figure 4-2. Site information needs for evaluation of corrective-action alternatives.

	Hydrogeologic characteristics												Geographic and topographic characteristics								Land and water use patterns			
Technology	Soil profiles	Soil physical properties	Soil chemical properties	Depth to bedrock	Depth to ground water	Aquifer physical properties	Ground-water flow rate (volume)	Ground-water flow direction	Recharge areas	Recharge rates	Aquifer characteristics	Natural ground-water quality	Precipitation	Temperature	Evapotranspiration	Topography	Accessibility	Site size	Proximity to surface water	Proximity to human interfaces	Current water-use patterns	Future water-use patterns	Current land-use patterns	Growth projections
Removal/excavation of tank, soil and sediment																								
Tank removal	●													●		●	●							
Soil excavation	●	●		●	●									●		●	●							
Sediment removal	●													●		●	●							
Onsite and offsite treatment and disposal of contaminants																								
Solidification/stabilization													●	●	●	●	●	●	●	●				
Landfilling	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	●	●	●	●	●	
Landfarming	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	●	●	●	●	●	
Soil washing	●	●	●		●								●	●		●	●	●		●	●	●	●	
Thermal destruction	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
Aqueous waste treatment	●	●	●										●	●	●	●	●	●	●	●	●	●	●	
Deep well injection	●	●	●	●	●	●	●	●	●	●	●	●				●	●			●	●	●	●	
Free product recovery																								
Dual pump systems	●	●		●	●	●	●	●	●	●	●	●	●				●							
Floating filter pumps	●	●		●	●	●	●	●	●	●	●	●	●				●							
Surface oil/water separators	●	●		●	●	●	●	●	●	●	●	●	●			●	●	●		●				
Ground-water recovery systems																								
Ground-water pumping	●	●		●	●	●	●	●	●	●	●	●	●				●				●	●	●	●
Subsurface drains	●	●		●	●	●	●	●	●	●	●	●	●				●				●	●	●	●
Subsurface barriers																								
Slurry walls	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●			●	●	●	●
Grouting	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●			●	●	●	●
Sheet piles	●	●	●	●	●	●	●	●	●	●	●	●	●			●	●	●			●	●	●	●
Hydraulic barriers	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●			●	●	●	●
In situ treatment																								
Soil flushing	●	●	●	●	●	●	●	●	●	●	●	●	●	●			●	●		●				
Biostimulation	●	●	●	●	●	●	●	●	●	●	●	●	●	●			●	●		●				
Chemical treatment	●	●	●	●	●	●	●	●	●	●	●	●	●	●			●	●		●				
Physical treatment	●	●	●	●	●	●	●	●	●	●	●	●	●	●			●	●		●				

Figure 4-2. (Continued)

Technology	Hydrogeologic characteristics												Geographic and topographic characteristics								Land and water use patterns			
	Soil profiles	Soil physical properties	Soil chemical properties	Depth to bedrock	Depth to ground water	Aquifer physical properties	Ground-water flow rate (volume)	Ground-water flow direction	Recharge areas	Recharge rates	Aquifer characteristics	Natural ground-water quality	Precipitation	Temperature	Evapotranspiration	Topography	Accessibility	Site size	Proximity to surface water	Proximity to human interfaces	Current water-use patterns	Future water-use patterns	Current land-use patterns	Growth projections
Ground-water treatment																								
Air stripping							●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Carbon adsorption							●		●	●	●	●	●		●	●	●	●	●	●	●	●	●	●
Biological treatment							●		●	●	●	●	●		●	●	●	●	●	●	●	●	●	●
Precipitation/flocculation/sedimentation							●		●	●	●	●	●		●	●	●	●	●	●	●	●	●	●
Dissolved air flotation							●		●	●	●	●	●		●	●	●	●	●	●	●	●	●	●
Granular media filtration							●		●	●	●	●	●		●	●	●	●	●	●	●	●	●	●
Ion exchange/resin adsorption							●		●	●	●	●	●		●	●	●	●	●	●	●	●	●	●
Oxidation/reduction							●		●	●	●	●	●		●	●	●	●	●	●	●	●	●	●
Neutralization							●		●	●	●	●	●		●	●	●	●	●	●	●	●	●	●
Steam stripping							●		●	●	●	●	●		●	●	●	●	●	●	●	●	●	●
Reverse osmosis							●		●	●	●	●	●		●	●	●	●	●	●	●	●	●	●
Sludge dewatering							●		●	●	●	●	●		●	●	●	●	●	●	●	●	●	●
Vapor migration control, collection, and treatment																								
Passive collection systems	●	●	●										●			●	●	●		●			●	●
Active collection systems	●	●	●										●			●	●	●		●			●	●
Ventilation of structures	●	●	●										●			●	●	●		●			●	●
Adsorption	●	●	●										●			●	●	●		●			●	●
Flaring	●	●	●										●			●	●	●		●			●	●
Surface water/drainage controls																								
Diversion/collection systems	●	●							●		●	●	●		●	●	●	●	●	●	●	●	●	●
Grading	●	●							●		●	●	●		●	●	●	●	●	●	●	●	●	●
Capping	●	●							●		●	●	●		●	●	●	●	●	●	●	●	●	●
Revegetation	●	●							●		●	●	●		●	●	●	●	●	●	●	●	●	●
Restoration of contaminated water supplies and sewer lines																								
Alternative central water supplies							●				●	●	●	●	●	●	●	●	●	●	●	●	●	●
Alternative point-of-use water supplies							●				●	●	●	●	●	●	●	●	●	●	●	●	●	●
Treatment of central water supplies							●				●	●	●	●	●	●	●	●	●	●	●	●	●	●
Treatment of point-of-use water supplies							●				●	●	●	●	●	●	●	●	●	●	●	●	●	●
Replacement of water and sewer lines															●	●	●	●	●	●	●	●	●	●
Cleaning/restoration of water and sewer lines															●	●	●	●	●	●	●	●	●	●

Note: Technologies in bold type are likely to be used in response to UST releases at gasoline stations.

taminant samples for chemical and physical testing in the laboratory or by conducting in situ tests of hydrogeologic properties.

Geographic and Topographic Characteristics

An understanding of the general physical characteristics of a site is important. Surface attributes of a site should be identified because they can affect the subsurface environment both directly and indirectly. Climatic information (e.g., precipitation, temperature, and evapotranspiration) is also needed. Other factors having an impact on corrective actions are topography, accessibility, size of site, proximity to surface water, and proximity to population centers.

Water- and Land-Use Patterns

An understanding of surrounding water- and land-use patterns is essential to an assessment of the potential risk of affected populations. Current water usage and expected future requirements in the area of the UST release are important factors in determining the criticality of the threatened or polluted water resource.

4.1.2 Initial Corrective Actions

After the release has been evaluated, appropriate corrective actions should begin immediately. Initial corrective actions can be categorized as those actions that are directed at stabilizing a newly discovered or sudden release. During the implementation of initial corrective actions, efforts are focused on source control involving collection and containment of released material. The following is a list of those options that typically would apply in any initial corrective action response.

- Removal of remaining product from the leaking UST
- Collection of readily retrievable released substance
- Containment of release to minimize immediate threat to human health and environment
- Repair or removal of leaking tank
- Restriction of access to the site

Effective implementation of initial corrective actions commonly dictates that field deployment occur within hours of the discovered release. It is essential that early discovery and containment of any suspected leak occur as soon as possible so that recovery procedures may be initiated and the influence of any release can be minimized. Normally, the first action taken is the removal of any remaining product in the leaking UST. In addition, measures are often taken to minimize imminent and immediate risk to human health and the environment. Figure 4-3 presents a listing of options available for the initial response to typical UST release situations.

4.2 Permanent Corrective-Action Options

After the initial response, the focus of assessment and investigation activities turns toward the need for permanent corrective measures. In situations where the release poses no danger to ground-water resources, human health, and the environment, corrective action may be limited to pumping the tank and removing significantly contaminated soils. Figure 4-4 is a generic flow diagram showing the procedure for deciding what the permanent corrective-action approach should be. The appropriate local, State, and Federal agencies should be consulted for more specific corrective-action guidelines.

4.2.1 Assessment and Investigation to Determine Surrounding Land Use and Potential Impact on Public Health

Selection of the proper permanent corrective-action approach requires consideration of the physical geography of the site where the release occurred. For example, an underground tank leak at a corner gas station presents different problems from those encountered at a large industrial facility. Because gas stations are on small plots in residential or light commercial developments, several factors must be considered:

- Limited available land for implementing corrective action.
- Possible rapid offsite migration requiring easements to conduct offsite cleanup.
- High potential for public health impacts because of the proximity of densely populated areas.
- Implementation difficulties posed by the complexity of adjacent subsurface public-service facilities (e.g., sewers, water lines, and electric utilities).

Figure 4-5 presents a matrix of site problems commonly encountered and the appropriate corrective action.

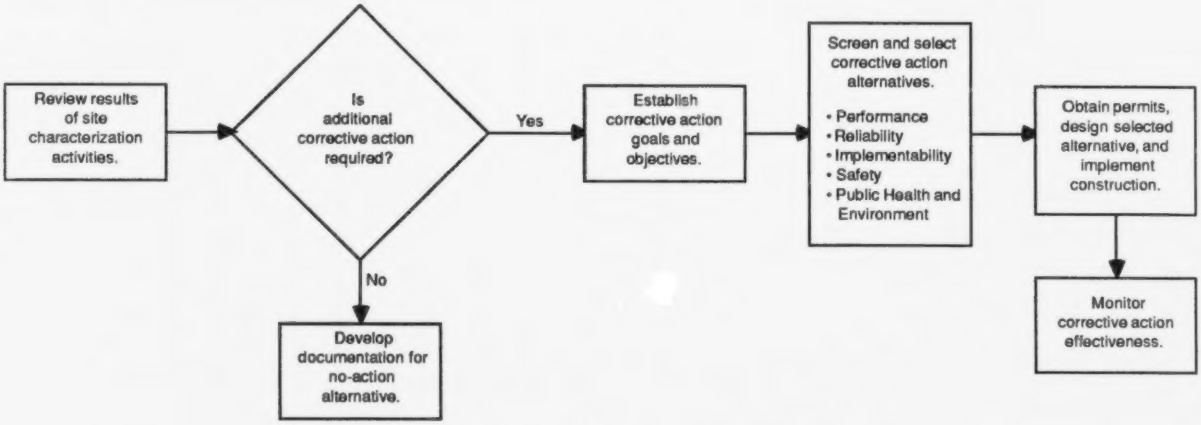
4.2.2 Factors Affecting Selection of Corrective Actions

After the appropriate actions for particular situations have been identified, several factors should be evaluated before a commitment is made to a particular approach. The extent of the evaluation will depend on the magnitude of the release and the sensitivity of the public to the available options. The factors that should be considered are broken down in four categories: 1) technical, 2) institutional, 3) human health and the environment, and 4) costs. The following subsections address each separately.

Figure 4-3. **Potential initial response situations and associated corrective actions.**

Situation	Tank repair/removal	Free product recovery	Ground-water recovery and treatment	Subsurface barriers	Soil excavation	Vapor migration control and collection	Sediment removal	Surface water diversion drainage	Alternative/treatment central water supply	Alternative/treatment point-of-use water supply	Restoration of utility, water, and sewer lines	Evacuation of nearby residents	Restricted egress/ingress
Ground-water contamination													
Existing public or private wells	●	●	●	●									
Potential future source of water supply	●	●	●	●	●								
Hydrologic connection to surface water	●	●	●	●									
Soil contamination													
Potential for direct human contact: nuisance or health hazard	●				●		●	●					
Agricultural use	●				●		●	●					
Potential source of future releases to ground water	●	●	●	●	●	●							
Surface-water contamination													
Drinking water supply	●	●	●	●					●	●	●		
Source or irrigation water	●	●	●	●					●	●	●		
Water-contact recreation	●							●					●
Commercial or sport fishing	●							●					●
Ecological habitat	●							●					
Other hazards													
Danger of fire or explosion	●					●						●	●
Property damage to nearby dwellings						●						●	●
Vapors in dwellings	●					●						●	●

Figure 4-4. **Permanent corrective-action process.**



Review results of site characterization activities.
Is additional corrective action required?
Yes
No
Develop documentation for no-action alternative.
Establish corrective action goals and objectives.
Screen and select corrective action alternatives.
• Performance
• Reliability
• Implementability
• Safety
• Public Health and Environment
Obtain permits, design selected alternative, and implement construction.
Monitor corrective action effectiveness.

Figure 4-5. **Matrix of permanent corrective action categories for specific site problems (EPA 1985a).**

	Corrective action categories									
	Removal/excavation of soil and sediments	Onsite and offsite treatment and disposal of contaminants	Free product recovery	Ground-water recovery systems	Subsurface barriers	In situ treatment	Ground-water treatment	Vapor migration control, collection, and treatment	Surface water/drainage controls	Restoration of contaminated water supplies and sewerlines
Volatilization of chemicals into air								●		
Hazardous particulates released to atmosphere	●							●		
Dust generation by heavy construction or other site activities										
Contaminated site run-off	●						●		●	
Erosion of surface by water									●	
Surface seepage of released substance	●		●						●	
Flood hazard or contact of surface water body with released substance	●								●	
Released substance migrating vertically or horizontally			●	●	●					
High water table which may result in ground-water contamination or interfere with other corrective action				●	●					
Precipitation infiltrating site and accelerating released substance migration						●			●	
Explosive or toxic vapors migrating laterally underground					●			●		
Contaminated surface water, ground water, or other aqueous or liquid waste	●	●		●	●	●	●			
Contaminated soils	●	●				●				
Toxic and/or explosive vapors that have been collected		●						●		
Contaminated stream banks and sediments	●	●								
Contaminated drinking water distribution system		●		●	●		●			●
Contaminated utilities								●		●
Free product in ground water and soils	●	●	●	●	●	●	●			

4.2.2.1 Technical Factors

Performance

Two aspects of corrective actions determine their desirability from a performance standpoint: effectiveness and useful life.

Effectiveness refers to how well the corrective action technology accomplishes its intended purpose, such as containment, diversion, removal, destruction, or treatment. The effectiveness of available alternatives should be determined either through design specifications or by performance evaluation (EPA 1985a).

Useful life refers to the length of time a corrective action technology can maintain the desired level of effectiveness. Some corrective action technologies deteriorate with time. Such deterioration can sometimes be slowed down through proper system operation and maintenance, but the technology may eventually require replacement. Each corrective action alternative should be evaluated in terms of the projected service lives of its component technologies (EPA 1985a).

Reliability

Two aspects of UST corrective action technologies that provide information about reliability are their operation and maintenance requirements (i.e., frequency and complexity) and their demonstrated reliability at similar UST sites (EPA 1985a). Demonstrated and expected reliability is a way of measuring the risk and effect of failure. The engineer should evaluate whether the considered technologies have been used effectively at similar sites; whether a combination of technologies has been used effectively; whether the failure of any one technology has an immediate impact on receptors; and whether the alternative has the flexibility to deal with uncontrollable changes at the site.

Implementation

Another important consideration in the selection process is whether the corrective action can be implemented with relative ease, i.e., whether it can be constructed or installed within the time frame required to achieve the desired results.

4.2.2.2 Institutional Factors (Regulatory Compliance)

The effects of Federal, state, and local standards and other institutional considerations on the implementation and operational timing should be analyzed. Regulatory programs under the Resource Conservation and Recovery Act (RCRA) Subtitle I, the Safe Drinking Water Act (SDWA), the Federal Water Pollution Control Act (Clean Water Act or CWA), the Toxic Substance Control Act (TSCA), and the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) will often have some impact on UST corrective actions (EPA 1985a).

4.2.2.3 Human Health and Environmental Factors

Safety

Each corrective action alternative should be evaluated with regard to safety. This evaluation should include threats to the safety of nearby communities and environment as well as those to workers during implementation. Safety factors to consider are fire, explosion, and exposure to hazardous substances (EPA 1985a).

Human Health and the Environment

Consideration should be given to the effect on human health and any beneficial or adverse environmental impacts in the selection of corrective actions. The objective should be to improve public health and the environment to the extent site-specific conditions permit (EPA 1985a).

4.2.2.4 Costs

Both capital and operation and maintenance costs should be estimated. The estimate should reflect the scale of the planned corrective actions. Estimates for large, long-term corrective action options will require more detail. Application of a particular option is determined by conditions both internal and external to the site, such as the location of underground utilities, depth of the water table, heterogeneity of subsurface materials, and the site itself (i.e., whether it lies in a remote area or a congested urban area)(EPA 1985a).

4.3 Risk Analysis

Before a commitment is made to a specific corrective action strategy, the levels of acceptable risk should be established to assist in the determination of criteria for meeting cleanup objectives. Data obtained during site characterization activities and technology performance evaluations are used in this determination. An analysis could be made to forecast concentrations of the released substance in the media of concern. Based on toxicty data and regulatory and environmental standards, the relative human and environmental hazard posed by exposure to various concentration levels can be assessed. The combination of the likelihood of exposure to the released substance and the hazard posed by such exposure provides a measurement of the relative risk involved. This relative risk factor could then be used to establish cleanup goals and to assist in the selection and design of appropriate corrective-action technologies.

Section 5
Technology Profiles

This section describes the corrective action technologies used to clean up leaking USTs. Under each technology, it also presents information on availability, applicability, design, and construction implementation. When available, general cost data updated to mid-1986 dollars are included. The technologies covered are appropriate for response to petroleum and hazardous chemical releases. Many of the technologies apply to both initial response and permanent corrective actions.

Several factors affect the selection and application of the technologies described. Figures 5-1 and 5-2 present flow charts of the selection procedures for the initial response and permanent corrective actions, respectively.

The intent of Figure 5-1 is to show the technologies that are generally associated with an initial response action to assist the user in selecting the appropriate actions. Selection, of course, will depend on evaluation of the site and the characteristics of the product released.

Figure 5-1. Flow chart of activities involved in the initial response to an UST release.

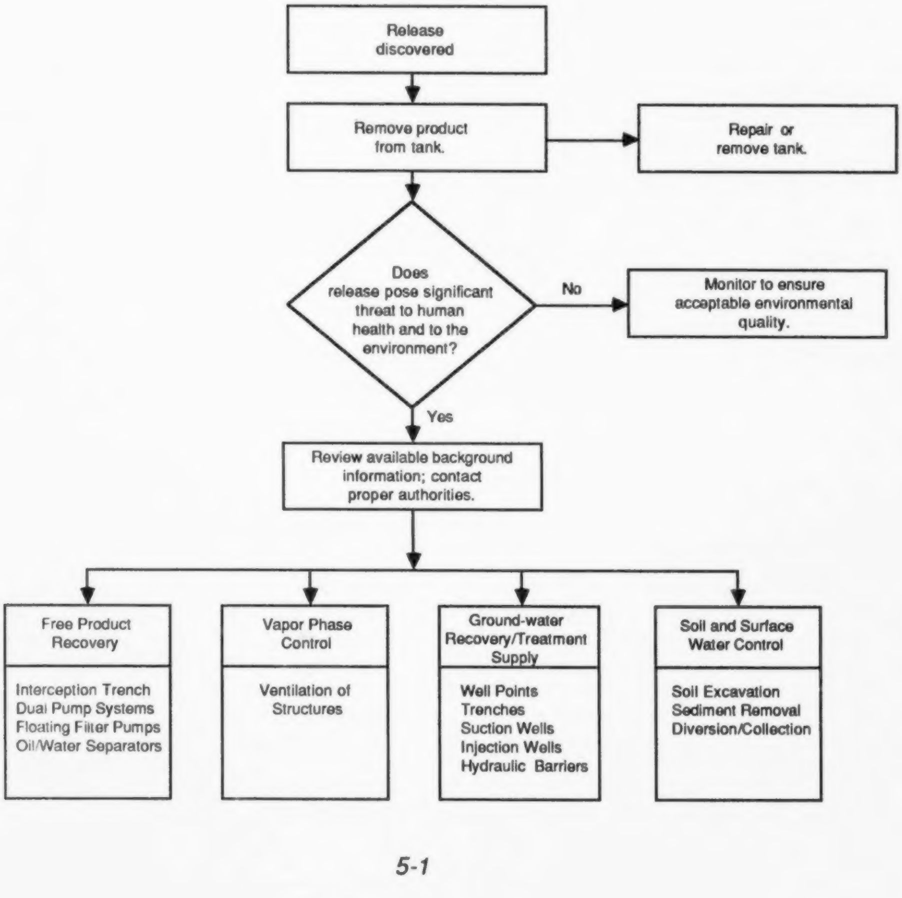
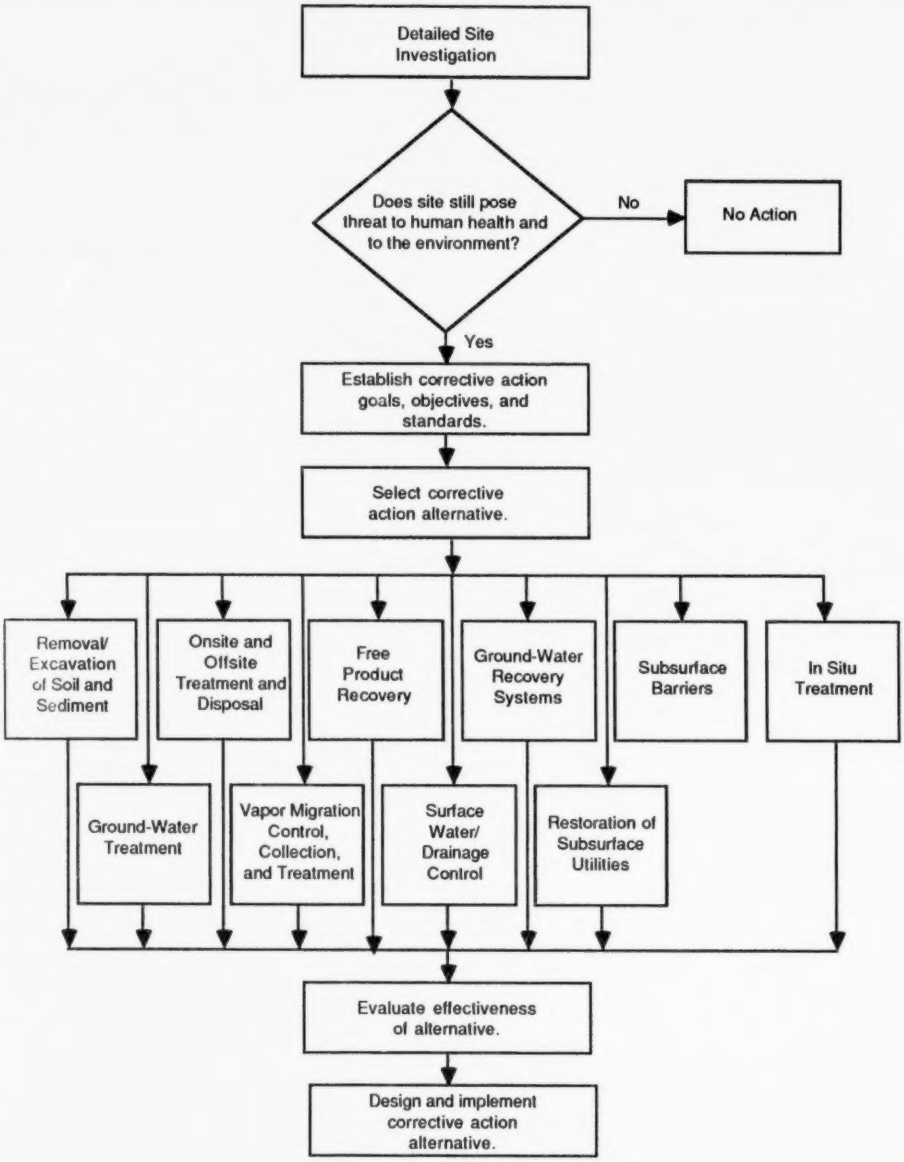

Release discovered
Remove product from tank.
Repair or remove tank.
Does release pose significant threat to human health and to the environment?
No
Monitor to ensure acceptable environmental quality.
Yes
Review available background information; contact proper authorities.
Free Product Recovery
Interception Trench
Dual Pump Systems
Floating Filter Pumps
Oil/Water Separators
Vapor Phase Control
Ventilation of Structures
Ground-water Recovery/Treatment Supply
Well Points
Trenches
Suction Wells
Injection Wells
Hydraulic Barriers
Soil and Surface Water Control
Soil Excavation
Sediment Removal
Diversion/Collection

Figure 5-2. **Flow chart of permanent corrective action in response to an UST release.**


Detailed Site Investigation
Does site still pose threat to human health and to the environment?
No
No Action
Yes
Establish corrective action goals, objectives, and standards.
Select corrective action alternative.
Removal/ Excavation of Soil and Sediment
Onsite and Offsite Treatment and Disposal
Free Product Recovery
Ground-Water Recovery Systems
Subsurface Barriers
In Situ Treatment
Ground-Water Treatment
Vapor Migration Control, Collection, and Treatment
Surface Water/ Drainage Control
Restoration of Subsurface Utilities
Evaluate effectiveness of alternative.
Design and implement corrective action alternative.

Upon completion of the initial-response activities (sometimes during), it often becomes apparent that more comprehensive site cleanup is needed. When this occurs, the flow chart of procedures presented in Figure 5-2 is applicable for permanent corrective actions. Permanent corrective measures are usually more costly and require more data for effective design and implementation as they are directed at arriving at a final solution to the problems created by a leaking UST.

Figure 5-3 presents applicable corrective-action technologies for four hypothetical UST release scenarios, two related to petroleum products and two to hazardous substances. The reader will note that some technologies apply to all four scenarios, (e.g., tank removal), whereas others apply only to one scenario (e.g., oxidation/reduction). Most technologies are adaptable to the release of both petroleum and chemical products.

Figure 5-3. **Potentially applicable corrective action technologies relative to release volume and chemical characteristics.**

Technology	Small- to moderate-volume recent gasoline/ petroleum release (gas station/tank farms)	Large-volume or long-term chronic gasoline/ petroleum release (gas station/tank farms)	Release from tanks containing hazardous substances (organic)	Release from tanks containing hazardous substances (inorganic)
Removal/excavation of tank, soil, and sediment				
Tank removal	●	●	●	●
Soil excavation	●	●	●	●
Sediment removal		●	●	●
Onsite and offsite treatment and disposal of contaminants				
Solidification/stabilization		●	●	●
Landfilling				●
Landfarming	●	●	●	●
Soil washing				●
Thermal destruction		●	●	
Aqueous waste treatment	●	●	●	●
Deep well injection				
Free product recovery				
Dual pump systems	●	●	●	●
Floating filter pumps	●	●	●	●
Surface oil/water separators	●	●	●	
Ground-water recovery systems				
Ground-water pumping	●	●	●	●
Subsurface drains	●	●	●	●
Subsurface barriers				
Slurry walls		●	●	●
Grouting		●	●	●
Sheet piles				
Hydraulic barriers	●	●	●	●
In situ treatment				
Chemical treatment				
Physical treatment			●	●
Soil flushing	●	●	●	●
Biostimulation	●	●	●	●
Ground-water treatment				
Air stripping	●	●	●	
Carbon adsorption	●	●	●	
Biological treatment	●	●	●	
Precipitation/flocculation/sedimentation				●
Dissolved air flotation				●
Granular media filtration				●
Ion exchange/resin adsorption				●
Oxidation/reduction				●
Neutralization				●
Steam stripping			●	
Reverse osmosis				●
Sludge dewatering				●
Vapor migration control, collection, and treatment				
Passive collection systems		●	●	
Active collection systems		●	●	
Ventilation of structures	●	●	●	
Adsorption			●	
Flaring				
Surface water/drainage controls				
Diversion/collection systems	●	●	●	●
Grading	●	●	●	●
Capping		●	●	●
Revegetation	●	●	●	●
Restoration of contaminated water supplies and sewer lines				
Alternative central water supplies		●	●	●
Alternative point-of-use water supplies	●	●	●	●
Treatment of central water supplies		●	●	●
Treatment of point-of-use water supplies		●	●	●
Replacement of water and sewer lines		●	●	
Cleaning/restoration of water and sewer lines	●	●	●	●

Although release characteristics and facility design variables are taken into account in Figure 5-3, the most important considerations are the volume and type of substance released and constraining site features that can hinder or prevent effective implementation of a technology. To a lesser extent, consideration was also given to the financial ability of responsible parties to implement certain technologies and to the impacts on facility production or service operations. Case histories and members of the American Petroleum Institute provided valuable information relative to corrective action technologies currently being implemented.

Figure 5-3 is intended as a guide for the review of technologies given certain site characteristics; however, it is not a technology selection matrix for corrective action responses. Far more site-specific analysis must be conducted before corrective action technologies and alternatives are selected for permanent cleanup of a release from a leaking UST.

5.1 Tank Removal, Abandonment, and Rehabilitation Removal/ Excavation of Soil and Sediments

The excavation and removal of leaking tanks and contaminated soil and sediment will apply to almost all leaking underground tank incidents. These actions, however, can become cost-prohibitive at great depths or in complex hydrogeologic environments. Factors that must be considered in the decision-making process include the mobility of the wastes, the feasibility of onsite containment or in situ treatment, and the cost of disposing of the waste (or tank) or decontaminating it once it has been excavated. Tank rehabilitation is a more appropriate approach for small leaks in relatively new tank systems or for nonleaking but high-risk tanks.

5.1.1 Tank Removal, Abandonment, and Rehabilitation

5.1.1.1 General Description

Determining whether to abandon a tank in place or to remove it normally would depend on the location of the tank, local regulations, availability of equipment, labor, materials, and associated costs. Current regulations, however, preclude consideration of the abandonment of a leaking underground storage tank. Such action would not meet the minimum standards outlined in the 1984 RCRA amendments and subsequent EPA Subpart I regulations. Inasmuch as corrective action will be required in response to all releases of regulated substances, even proper decontamination and in-place abandonment of a leaking UST seems impractible (A leaking tank would be almost impossible to decontaminate in place). Furthermore, USTs must be sealed in a manner that will prevent future releases. This may be an impossible task for in-place abandoned tanks. Therefore, only tank removal and rehabilitation are discussed in this section.

5.1.1.2 Application/Availability

The most common form of rehabilitation for steel tanks entails lining the interior with an epoxy-based resin, isophthalic polyester-based resin, or some other acceptable coating. Lining, however, does not add significant structural strength to a tank and should not be used under the following conditions: 1) open seams more than 3 inches long, 2) perforations larger than about 1 inch in diameter, or 3) more than five perforations in a given square foot of surface area (Cheremsinoff et al. 1986). Tanks having any of these shortcomings should be removed. Tank lining is performed by numerous companies and company certification may be required in some States.

The repair or rehabilitation of fiberglass-reinforced plastic (FRP) tanks typically involved patching holes or cracks in the tank shell or end caps or repairing or replacing crushed or cracked ribs. The primary criterion typically used to determine whether an FRP tank should be repaired or replaced is economics, unless the damage is so great that repair is not feasible or practical. Before rehabilitation of an FRP tank is attempted, the tank manufacturer should be consulted (New York DEC, undated).

5.1.1.3 Design and Construction Considerations

Tank Rehabilitation

Proper procedures for preparing the tank for opening and entry are essential to ensure the safety of all persons involved in the tank rehabilitation process. The following activities are especially important (API 1981):

- Controlling sources of ignition
- Removal of liquid product
- Removal of flammable vapors
- Testing of vapor concentrations

Guidelines for these activities can be found in the referenced API publication.

If no manway or hatch exists, an 18 in. x 18 in. (minimum) hole can be cut in the tank top (steel) or tank end cap (FRP) with explosion-proof tools. Safety demands that persons entering an underground tank for habilitation activities be equipped with positive air displacement equipment with full face mask and wear a safety harness attached to a safety line.

Proper preparation of the tank interior is critical to lining or patching a tank. This entails the following steps (New York DEC, undated):

1) Sludge removal--Sludge that has accumulated in the tank must be collected and properly disposed of.

2) Surface inspections--After the sludge has been removed, the tank must be carefully inspected to ensure that it meets the structural requirements for rehabilitation.

3) Sand blasting--The entire internal surface of the tank must be sand blasted completely free of rust, scale, and other foreign matter.

The lining material must be applied as soon as possible after the tank surface has been cleaned and sandblasted. The coating must be applied in strict accordance with manufacturer's specifications. After application, the new lining must be tested for the presence of air pockets and pinholes and allowed to cure fully before the tank is put back into operation. American Petroleum Institutes Publication 1631 provides details on the "Recommended Practice for the Interior Lining of Existing Steel Underground Storage Tanks" (See Bibliography).

After the tank contents and sludge have been emptied, cracks or holes in the shell or end cap of a fiberglass-reinforced plastic (FRP) tank can be repaired by the following steps (New York DEC, no date):

1) Surface preparation

2) Patching the damage

3) Curing the patch

Preparation of the surface and patching the damaged area should include extending the area of repair beyond the area of damage. In all cases, the tank manufacturer should be contacted prior to the repair of an FRP tank.

Tank Removal (API 1981)

The safe removal of underground tanks can be accomplished by taking the following eight steps:

1) Draining and flushing the piping into the tank.

2) Removing all flammable liquid from the tank that can be pumped out. A hand pump may be needed to remove the bottom few inches of product.

3) Digging down to the top of the tank.

4) Removing the fill (drop) tube; disconnecting the fill gage, product, and vent lines; capping or plugging open ends of lines that are not to be used further.

5) Temporarily plugging all tank openings and completing the excavation; removing the tank and placing it in a secure location; and blocking the tank to prevent movement.

Before degassing measures are undertaken, it is normally necessary to remove the tank from the ground because any product that may have leaked into the ground could reenter the tank. Extreme caution should be used during this procedure.

6) Removing vapors. The tank should be conditioned by one of the following methods, or as required by local codes, to ensure that no flammable, hazardous, or toxic vapors remain.

   a) If water is available and a suitable means for its disposal are available, the tank may be filled with water to expel vapors. While the tank is being filled with water, vapors will flow out of the tank and may surround the area. If the tank overflows, purged product also may flow out. Hence, all normal safety and pollution precautions regarding flammable, hazardous, or toxic liquids and vapors must be observed. When the tank is to be removed from the premises, the contaminated water should be removed and disposed of in accordance with regulations.

   b) If the method described in (a) is not practicable, the vapors in the tank may be made inert by adding solid carbon dioxide (dry ice) in the amount of 1.5 pounds per 100 gallons of tank capacity. The dry ice should be crushed and distributed evenly over the greatest possible area to secure rapid evaporation. Skin contact with dry ice should be avoided because it may produce burns. As the dry ice vaporizes, tank vapors will flow out of the tank and may surround the area. Hence, all safety precautions regarding flammable, hazardous, or toxic vapors should be observed. It must be ascertained that all of the dry ice has vaporized.

   c) Another alternate method is to ventilate the tank with air by use of a small gas exhauster operated with compressed air or by other suitable means. The flow of air in through an opening near one end of the tank and the discharge of the vapor-air mixture out of an opening near the opposite end will quickly remove the vapor. The vapor concentration in the tank can be checked with suitable instrumentation to determine when the tank is gas-free. While the tank is being ventilated, flammable, hazardous, or toxic vapors may flow from the tank, and proper handling or disposal procedures must be followed.

7) Plugging or capping of all holes after the tank has been freed of vapors and before the tank is moved from the site. Screwed (boiler) plugs should be used to plug any corrosion leak

holes. One plug should have a 1/8-inch vent hole to prevent the tank from being subjected to an excessive pressure differential caused by extreme temperature changes.

8) Finally, if size permits, securing the tank on a truck for transportation to the disposal site. The tank should be secured so that the 1/8-inch vent hole is located at the uppermost point on the tank.

If a tank remains at the site overnight or longer, additional vapor may be released from liquid held in the scale or sediment in the tank. Consequently, tanks should be removed from the premises as promptly as possible after these procedures have been completed.

5.1.1.4 Costs

Tank lining costs about $2000 for a 4000-gallon tank and $4000 to $5000 for a 10,000-gallon tank. An additional cost of $500 to $1000 per tank is required if a manway has to be constructed for tank entry (Cheremisinoff et al. 1986). Tank excavation/removal will usually range from $1000 to $2000. Tank preparation and testing prior to excavation will cost approximately $1000, and tank disposal could run as high as $2000 (Tusa 1986). All costs given are in 1986 dollars.

5.1.2 Soil Excavation (EPA 1985a)

5.1.2.1 General Description

The quantity of excavation required for a leaking UST occurrence depends on the volume of the leakage, the extent of the plume, and the remediation method chosen. The minimum amount will be for exploration work on the tank itself, and the total effort will be site-specific.

Excavation efforts not only expose the tank, but also permit removal of the pollution resulting from the release. Contaminated soils and earth materials are excavated with conventional construction equipment such as backhoes, draglines, front-end loaders, and even shovels. The type and size of the leak determines the type of equipment required to effect a satisfactory cleanup. Generally, excavation should be considered (1) when leaks are small and involve wastes with relatively low toxicity, (2) when a high hazard to drinking water supplies exists, (3) when insoluble wastes cannot be removed by pumping alone, or (4) when long-term treatment would be too costly.

The first step in the cleanup process involves excavation and proper disposal of the contaminated soils. Disposal could involve hauling the material to an approved hazardous waste dump site, incineration on or off site, or some other treatment technique (such as solidification, encapsulation, or solvent extraction and drying). Solidification of excavated materials can ultimately lead to reduced disposal costs if laboratory tests prove the solidified waste to be nonhazardous.

Excavation is ineffective as a total removal technique if the contaminants have already leached from the spill site. Factors such as soil types, ground and surface waters, and amount of precipitation after a spill can influence the degree to which a material has leached. Excavation of all contaminated substances (including ground water and strata through which it flows) is rarely performed because of the high costs associated with the transport and treatment or disposal of large volumes of soil.

5.1.2.2 Application/Availability

Remediation of a leak site usually entails excavation and removal of contaminated materials followed by land disposal or treatment. Although no absolute limitations are placed on the materials that can be excavated and removed, worker health and safety are strong considerations in the decision to excavate explosive, reactive, or highly toxic materials. Other factors that are considered include the mobility of the material, the feasibility of onsite containment or in situ treatment, and the cost of disposing of or decontaminating the soil after it has been excavated. A frequent practice is to excavate and remove contaminant "hot spots" and to use other remedial measures for less-contaminated soils. Excavation and removal apply to almost all site conditions; however, such actions may become cost-prohibitive at great depths or in complex hydrogeologic environments.

5.1.2.3 Design and Construction Considerations

Regardless of the kind of equipment used for excavation and handling, certain standard operating procedures and safety practices should be followed.

During the excavation of the contaminated soils, air monitoring should be conducted to determine the presence of unsafe levels of various hazardous constituents. Numerous portable direct reading instruments are available for this purpose. These include:

- Combustible gas detectors for measuring the lower explosive limit (lowest concentration of flammable gas that will explode, ignite, or burn when an ignition source exists).
- Oxygen meters for measuring the percentage of oxygen.
- Photoionization detectors, flame ionization detectors, infrared analyzers, and detector tubes for measuring gases and vapors.

As contaminated soils are excavated from the disposal area, they should be transferred to box trucks or to a temporary storage area, preferably a diked or bermed area lined with plastic or low-permeability clay. A layer of absorbent material should be placed on the bottom of the temporary storage area. Gas analyzers are often used to determine the approximate level of contamination in soils so they can be segregated according to their degree of contamination. Pools of liquid wastes or solvent materials should be removed promptly by the use of pumps.

5.1.2.4 Costs

Total excavation costs will depend on the amount of excavating required. Table 5-1 presents some unit costs for excavating with different pieces of equipment.

Table 5-1. Soil Excavation Costs*

Machine	Daily Capacity (yd ^{3})	Cost per Day ($)
Backhoe with 3.5-yd ^{3} bucket	1200	2025
Crane with 3.0-yd ^{3} bucket	900	1335
Wheel-mounted bucket loader	1480	1275
Towed scraper, 10-yd ^{3} capacity	440	1800
Dump truck, 12-yd ^{3} capacity, 1/4-mile haul	356	515

*Data from EPA 1985a.

5.1.3 Sediment Removal (EPA 1985a)

5.1.3.1 General Description

Contamination of the bottom sediments of streams, ponds, lakes, harbors, estuaries, and other water bodies may occur via several different pathways. The most likely pathway is via a ground-water plume extending to nearby water courses. Similarly, contaminated ground water may drain to surface water courses, and the transported pollutants may settle into or chemically bind with the bottom sediments.

Remedial techniques for contaminated sediments generally involve removal and subsequent treatment and disposal. During the removal of contaminated sediments, efforts must be made to minimize the threat of further environmental harm through resuspension of contaminants. Various techniques are available to control this problem. Control of turbidity (and contaminant resuspension) can be accomplished by modifying dredging equipment and using curtain barriers. Temporary diversion of water flow is also necessary. Measures such as containment and in situ treatment offer an alternative to removing the sediment; however, these measures are not yet well demonstrated.

5.1.3.2 Application/Availability

The process of removing bottom sediments from a water body is commonly known as dredging. This process, which has been used for many years to widen or deepen harbors and navigable waters, more recently has been applied to the removal of sediments contaminated by hazardous substances.

Dredging involves four tasks: 1) the loosening or dislodging of sediment by mechanically penetrating, grabbing, raking, cutting, drilling, blasting, or hydraulic scouring; 2) a lift action accomplished by mechanical devices such as buckets or by hydraulic suction; 3) the transport of dredged materials by pipeline, scows, hopper dredges, or trucks; and 4) the disposal of the dredged material.

Selection of equipment and methods is based on several practical considerations, including 1) type and amount of sediment to be dredged, 2) physical and hydrologic characteristics of the dredging site, 3) disposal options, and 4) availability of equipment.

5.1.3.3 Design and Construction Considerations

Mechanical dredging involves the use of such excavation equipment as backhoes, draglines, clamshells, and bucket-ladder dredges. Draglines and clamshells used for dredging are usually vessel-mounted, but they can be track-mounted and land-based.

The main advantage of mechanical dredging is that it allows removal of sediments at nearly in situ densities, which maximizes solids content and minimizes the scale of facilities required for transport, treatment, and disposal of the dredged material. A major disadvantage of this approach is that the direct application of mechanical force used to dislodge the material can result in high sediment resuspension (and therefore turbidity). Dredging of stream-bed sediments may be an undesirable corrective action technique because it will almost always release additional contamination into the water. Another disadvantage is that mechanical dredging is relatively ineffective in the removal of free or unabsorbed liquid contaminants. The productivity of this approach is also characteristically low.

Mechanical dredging generally can be applied in relatively shallow streams and rivers with low flow velocities. It can also be used to remove contaminated sediments deposited on dry river banks or in flood plains with less potential for resuspension of the contaminants.

Hydraulic dredges (including plain suction, dust-pan cutter head, and hopper dredges) remove and transport sediments in liquid slurry form by use of diesel- or electricity-powered hydraulic pumps with discharge pipes. Slurries containing 10 to 20 percent solids by weight are normally transported through pontoon-supported pipelines for distances up to several thousand meters.

A small hydraulic dredge known as the Mudcat is readily available in the United States from the National Car Rental Agency. The Mudcat can dredge a swath 8 feet wide by 18 inches thick in water as shallow as 19 inches and as deep as 15 feet. This hydraulic dredge has been tested in a hazardous material cleanup role and seems well suited to small cleaning jobs.

5.1.3.4 Costs

Estimated costs for dredging with a clamshell machine, not including disposal of sediment, is \$15/yd^3 of sediment. The cost for dredging with a Mudcat is estimated to be \$5/yd^3 of material removed, not including disposal.

5.2 Onsite and Offsite Treatment and Disposal of Contaminants

Onsite and offsite treatment and disposal technologies discussed in this section include solidification/stabilization, landfilling, landfarming, soil washing, thermal destruction, aqueous waste treatment, and deep-well injection. These technologies are applicable for both onsite and offsite use. Budgetary constraints, however, will usually determine whether onsite or offsite treatment/disposal is more feasible. Transportation costs often exceed actual treatment costs when a large volume of waste (contaminated soil) is involved.

5.2.1 Solidification/Stabilization

5.2.1.1 General Description

Solidification and stabilization methods of treating contaminated soils are applied to change the physical or leaching characteristics of the waste or to decrease its toxicity. In the solidification process, waste constituents are mechanically locked within a solidified matrix in the form of a crumbly soil-like mixture or a monolithic block similar to concrete. Although solidification improves the waste handling or other physical characteristics of the waste, it usually has little effect on the chemistry of the waste;therefore, leaching of waste constituents may occur in the future. Solidification may be accomplished by the use of portland cement or a lime-containing product (e.g., fly ash, ground blast furnace slag or cement kiln dust). Solidification can also be accomplished by the use of an organic polymer. In this case, the waste is mixed with a prepolymer and solidifies when a catalyst is added. In a third form, known as thermoplastic solidification, the waste is mixed with heated bitumin, paraffin, or polyethylene; this mixture solidifies upon cooling (Radian 1983). Stabilization is a chemical reaction that fixes substances in a matrix that results in a decrease in the solubility or toxicity of the hazardous waste constituents (EPA 1985a). Whereas stabilization reduces the solubility or mobility of waste constituents, it may not improve the physical handling characteristics. Therefore, solidification and stabilization are often combined to obtain the desired effects of both processes. This is accomplished by com-bining alkaline earth materials (such as lime, cement kiln dust, siliceous materials, or cement) with organic polymers and proprietary chemicals (EPA 1985a).

Solidification/stabilization processes fall into one of the following categories:

1) Cement-based
2) Lime-based
3) Thermoplastic
4) Organic polymer
5) Self-cementing

The first four of these processes are summarized in Table 5-2, along with their advantages and disadvantages.

5.2.1.2 Application/Availability

Cement- and lime-based processes capable of solidifying a wide range of materials are readily available. The materials must be amenable to forming a slurry with water. Thermoplastic and organic polymer processes, on the other hand, are often developed on a waste-specific basis and involve the use of proprietary chemicals and procedures.

5.2.1.3 Design and Construction Considerations

Cement- and lime-based processes require readily available equipment such as chemical storage hoppers, chemical feeding equipment, mixing equipment (ribbon blenders and single- and double-shaft mixers), and waste handling equipment (EPA 1985a). Thermoplastic and organic polymer processes require special equipment and trained operators, generally provided by vendors who are conducting some solidification proprietary processes.

Lime-based solidification also can be conducted on a batch basis in drums. In addition to chemical storage and batching equipment, drum handling and mixing systems are needed. Some firms have developed drum kits. In this type of application, earth-moving equipment (backhoes, shovels, etc.) are required in addition to chemical storage and mixing equipment.

Table 5-2. Solidification/Stabilization Processes*

Process	Description	Advantages	Disadvantages
Cement-based	Slurry of wastes and water is mixed with portland cement to form a solid	Low costs; readily available mixing equipment; relatively simple process; suitable for use with metals	Solids are suspended, not chemically bound; therefore are subject to leaching; doubles waste volume; requires secondary containment; incompatible with many wastes (organics, some sodium salts, silts, clays, and coal or lignite).
Lime-based	Waste is reacted with lime and a fine-grained siliceous material (fly ash, ground blast furnace slag, cement kiln dust) to form a solid	Low cost; readily available mixing equipment; suitable for power-plant wastes (FGD sludges, etc.) as well as a wide range of industrial wastes, including metals, waste oil, and solvents	Increases waste volume; may be subject to leaching; requires secondary containment
Thermoplastic	Waste is dried, heated, and dispensed through a heated plastic matrix of asphalt bitumen, paraffin, or polyethylene	Less increase in volume than with cement- or lime-based processes; reduced leaching relative to cement- or lime-based processes; suitable for radioactive wastes and some industrial wastes	Wastes must be dried before use; high equipment costs; high energy costs; requires trained operators; incompatible with oxidizers, some solvents and greases, some salt, and chelating/complexing agents; requires secondary containment
Organic polymers	Waste is mixed with a prepolymer and a catalyst that causes solidification through formation of a sponge-like polymer matrix; urea-formaldehyde or vinyl ester-styrene polymers are used	Suitable for insoluble solids; very successful in limited applications	Pollutants are not chemically bound, subject to leaching; strongly acidic leach water may be produced; requires special equipment and operators; some of the catalysts used are corrosive; harmful vapors may be produced; incompatible with oxidizers and some organics; some resins are biodegradable and decompose with time

* Data from EPA 1985a.

5.2.1.4 Costs

Solidification/stabilization costs vary widely with the specific wastes and process used; however, some general guidelines are available. Table 5-3 shows approximate costs for some solidification processes.

Table 5-4 presents another cost summary, which compares costs for in-drum and in situ stabilization/solidification alternatives.

Table 5-3. Solidification Costs

Solidification Agent	Design Basis	Cost ($)
Cement-based	Cost of cement only; transportation highly site-specific	58 to 81/ton
Lime-based	Site-specific	0.03 to 0.15/ton
Thermoplastic		Cost not available; contact Werner and Pfleiderer Corp., Ramsey, or other vendors
Organic polymer		Cost not available; contact Todds Shipyards Corp., Galveston, TX, or other
Self-cementing	Cost for fixation of FGD sludge	2.00 to 2.75/ton

5.2.2 Landfilling

5.2.2.1 General Description

Landfilling is the burial of wastes in the ground. Hazardous waste landfills are constructed of lined cells with leachate collection systems, gas control systems, run-on/runoff controls, and ground-water monitoring systems. Landfilling has historically been the method

Table 5-4. Summary Comparison of Relative 1986 Costs of Stabilization/Solidification Alternatives[*]

		Plant Mixing [§]		
Parameter	In-drum[†]	In situ[‡]	Pumpable	Nonpumpable
Metering and mixing efficiency	Good	Fair	Excellent	Excellent
Processing days required	374	4	10	14
Cost//ton ($)				
Reagent	25.12 (9%)[¶]	21.84 (63%)	21.84 (53%)	21.84 (42%)
Labor and per diem	62.74 (23%)	1.45 (4%)	4.08 (10%)	7.38 (14%)
Equipment rental	45.63 (17%)	1.47 (4%)	4.18 (10%)	8.03 (16%)
Used drums at $11/drum	(59.25 (21%)	-	-	-
Mobilization-demobilization	19.27 (7%)	1.68 (5%)	1.52 (4%)	2.40 (5%)
Cost of treatment demobilization	$212.01	26.44	31.62	39.65
Profit and overhead	63.58 (23%)	6.91 (23%)	9.54 (23%)	11.90 (23%)
TOTAL COST/TON	$275.59	$33.35	$41.16	$51.55

[*] Data from Cullinane and Jones 1985; costs were updated to 1986 dollars by use of the 1986 ENR Construction Cost Index.
[†] Assumes 49 gallons of untreated waste per drum and an average processing rate of 4.5 drums per hour.
[‡] Assumes wastes would be mixed by backhoe in a lagoon and left there. Site is located 200 miles from the nearest equipment.
[§] Assumes pumpable sludge has a daily throughput of 250 yd^3/day and nonpumpable sludge has a throughput of 180 yd^3/day. Site is located 200 miles from the nearest equipment.
[¶] Percentage of total cost/ton for that alternative.

of choice for disposal of hazardous wastes; however, the 1984 Hazardous and Solid Waste Amendments (HSWA) to RCRA have reduced the availability of landfilling as an option.

5.2.2.2 Application/Availability

The 1984 HSWA Amendments to RCRA established a hierarchy of hazardous waste management methods. The legislation shows a strong preference for treatment, recycling, or destruction as opposed to landfilling. The Amendments require that EPA review wastes; if their disposal on land is not safe, landfilling of that waste will be prohibited unless no other alternative exists. As this review of wastes proceeds, the landfilling of more waste types is expected to be prohibited. Currently, liquids are banned in landfills. Listed dioxin- and solvent-containing wastes also were prohibited effective November 8, 1986. The "California List" of hazardous wastes goes into effect July 8, 1987, unless EPA sets treatment levels. This list includes liquid wastes containing specified amounts of free cyanide, metals, polychlorinated biphenyls, and halogenated organics. In addition, the limited number of permitted hazardous waste landfills often requires that hazardous wastes be transported over long distances for land disposal.

5.2.2.3 Design and Construction Considerations

The 1984 HSWA Amendments to RCRA are specific in the design requirements for hazardous waste landfills. New or expanded landfills must have double liners, leachate collection systems, and ground-water monitoring systems. The leachate collection system must be above and between the liners.

5.2.2.4 Costs

Landfilling costs vary with the type and toxicity of the waste and by disposal site. Many industrial wastes can be landfilled for $40 to $85/ton. Ignitable wastes generally cost about $125/ton. Fees for highly toxic wastes are about $245/ton (EPA 1985a). These fees are in addition to transportation costs, which generally run about $3/mile for each load.

5.2.3 Landfarming

5.2.3.1 General Description

Landfarming consists of applying wastes to the soil surface, with or without mixing in the top layers of soil. The application of selected wastes to soil allows degradation or immobilization to occur. Additional agents may be applied to provide nutrients, to control moisture, or to accomplish chemical or biological reactions. Immobilization reduces the rate of release of contaminants from soil to reduce exposure. The mechanisms of sorption, ion exchange, and precipitation produce immobilization (Sims et al. 1985). Metals can be immobilized through sorption by the addition of adsorbents (e.g., straw, sawdust, peanut hulls, bark, and activated carbon) or metal complexing agents (e.g., Tetran), which are tilled into the soil with the waste (Sims et al. 1985). Some organics can be sorbed onto soil by the addition of organic material such as sewage sludge; this is most effective in soils such as sands or gravels, which are naturally low in organic matter. Immobilization through ion exchange is accomplished by the landfarming of wastes onto clay soils or by the addition of synthetic resins (e.g., Chelex 100 or Dower 1-X8) or zeolites to the soil. Zeolites are crystalline-hydrated alumino silicates used to adsorb heavy metal cations. Precipitating agents such as lime, limestone, trebel superphosphate, and calcium sulfide can be added to heavy metal wastes and soils to form insoluble metal precipitates.

Chemical degradation includes oxidation, reduction, and polymerization reactions to render the wastes less toxic or less mobile. Oxidizing agents (e.g., ozone and hydrogen peroxide) or reducing agents (e.g., catalyzed metal powders of iron, zinc, or aluminum) can be added to soils by spray, injection, or tilling. For example, ferrous iron can be added to surface soils to reduce hexavalent chromium to the less toxic trivalent form. Organics that can be polymerized (e.g., styrene, vinyl chloride, isoprene, acrylonitrile, or methyl methacrylate) can be treated by mixing them in soil with iron and sulfates. Chemical degradation techniques in soil should be tested in laboratory bench-scale and field pilot-scale experiments before full-scale landfarming is attempted.

Some wastes may biodegrade naturally in soils, or biodegradation may be accomplished by adding specific microorganisms selected for their ability to degrade a given waste type. In either case, landfarming treatment consists of applying the waste to the soil and optimizing degradation through addition of nutrients, water, air, or agents to control soil pH.

5.2.3.2 Application/Availability

Landfarming normally is limited to organic wastes that are biodegradable, such as petroleum sludges, and to metals that can be immobilized in soil. Hazardous waste regulations require that a demonstration program be conducted before a permit can be issued. For some wastes, laboratory bench-scale testing must be performed prior to field studies. Landfarming operations also must comply with monitoring regulations.

5.2.3.3 Design and Construction Considerations

Landfarming can involve the application of wastes onto the surface only, or it can involve tilling the waste into the first few inches of soil.

Solid or semisolid wastes or reagents can be applied with truck-mounted, hitch-mounted, or tractor-drawn spreaders. Liquids can be applied with hydraulic sprayers or subsurface injectors. Reagents can be mixed with plows, rotary tillers, disc harrows, spike harrows, or spring-tooth harrows (Sims et al. 1985). Moisture can be added by sprinklers, irrigation pipes, or trenches. Aeration is accomplished by tilling.

5.2.3.4 Costs

Costs vary widely with the cost of the land, labor, and reagents required at a given site. Using a manure spreader costs about $5/yd^3. Other significant costs include:

- Purchase of the land
- Excavation of wastes
- Development and implementation of a health and safety program
- Sampling and analysis of the soil

5.2.4 Soil Washing

5.2.4.1 General Description

Soil washing is the extraction of contaminants from excavated soil by mixing the soil with water, solvents, surfactants, or chelating agents. The contaminated water or solution is then treated for removal of contaminants. Heavily contaminated soils are commonly treated several times in a multistage countercurrent treatment system. A similar process for in situ treatment of soils, referred to as soil flushing, is described in Subsection 5.6.1.

5.2.4.2 Application/Availability

Soil washing is applicable to the treatment of heavy metals, halogenated aliphatics (e.g., trichloroethylene, trichloroethanes, chloroform), aromatics (e.g., benzene, toluene, cresol, phenols), and volatile hydrocarbons such as gasoline. Surfactants have been used successfully to remove hydrophobic organics from soils (e.g., polynuclear aromatic hydrocarbons, aliphatic and aromatic hydrocarbons, polychlorinated biphenyls, and chlorinated phenol mixtures).

Soil washing is an appropriate technique when a single waste type is involved. Soils that are most amenable to soil washing are those with a low organic content, a low cation exchange capacity, and a permeability greater than 1×10^{-4} cm/s. A sandy porous soil is more easily treated than clay or silt.

5.2.4.3 Design and Construction Considerations

All soil-washing systems are mobile and are set up at the contaminated site, as the cost of moving the soil would make this system uneconomical. A mobile soil-washing/wastewater-treatment system developed by the EPA has been demonstrated at hazardous waste sites. A flow diagram of this EPA system is shown in Figure 5-4. Several variations on this design that are currently being used or demonstrated for cleanup of hazardous wastes at Superfund sites have the potential for use at UST sites as well.

5.2.4.4 Costs

To date, much of the soil washing has been done on an experimental basis. The soil-washing system used at a Superfund site in Wisconsin cost about \$150 to $\$200/\text{yd}^3$; much of this amount was for the water-treatment system. (These are 1986 costs.)

5.2.5 Thermal Destruction

5.2.5.1 General Description

Thermal destruction is the high-temperature oxidation of recovered product and wastes. Under controlled conditions of time, temperature, and turbulence, wastes can be degraded to simple end products such as carbon dioxide (CO_2), water vapor, sulfur dioxide (SO_2), nitrogen oxides (NO_x), hydrochloric acid (HCl) vapors, and particulates. Many types of incinerators can be used for thermal destruction of waste oils, recovered products from leaks or spills that cannot be reused, and other wastes. The most commonly used incinerators (liquid-injection, rotary-kiln, fluidized-bed, and multiple-hearth) are described in Table 5-5.

In addition to these standard technologies, emerging technologies for thermal destruction include the following: molten-salt, wet-air oxidation, plasma-arch torch, circulating-bed, high-temperature fluid wall, pyrolysis, supercritical water, advanced electrical reactor, and vertical tube reactor.

Figure 5-4. Flow diagram for EPA mobile soil washer (EPA 1985c).

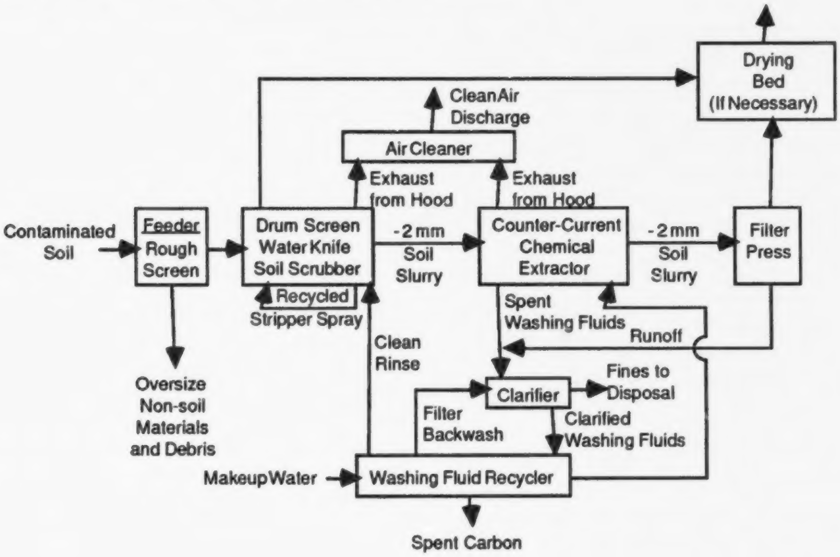

Drying Bed (If Necessary)
Clean Air Discharge
Air Cleaner
Exhaust from Hood
Exhaust from Hood
Contaminated Soil
Feeder Rough Screen
Drum Screen Water Knife Soil Scrubber
-2 mm Soil Slurry
Counter-Current Chemical Extractor
-2 mm Soil Slurry
Filter Press
Recycled Stripper Spray
Spent Washing Fluids
Runoff
Clean Rinse
Oversize Non-soil Materials and Debris
Fines to Disposal
Clarifier
Filter Backwash
Clarified Washing Fluids
Makeup Water
Washing Fluid Recycler
Spent Carbon

Table 5-5. Summary of Commonly Used Incineration Technologies*

Type	Process Principle	Application	Combustion Temperature	Residence Time
Rotary-kiln	Waste is burned in a rotating refractory cylinder	Any combustible solid, liquid, or gas	1500° to 3000°F	Seconds for gases; hours for liquids and solids
Single-chamber/ liquid-injection	Wastes are atomized with high-pressure air or steam and burned in suspension	Liquids and slurries that can be pumped	1300° to 3000°F	0.1 to 1 second
Multiple-hearth	Wastes descend through several grates to be burned in increasingly hotter combustion zones	Sludges and granulated solid wastes	1400° to 1800°F	Up to several hours
Fluidized-bed	Waste is injected into an agitated bed of heated inert particles. Heat is efficiently transferred to the wastes during combustion	Organic liquids, gases, and granular or well processed solids	1400° to 1600°F	Seconds for gases and liquids; minutes for solids

* Data from State of California 1981.

5.2.5.2 Application/Availability

Liquid-injection incinerators can thermally degrade a wide variety of wastes (pumpable liquids or sludges and gaseous wastes). A liquid or sludge waste must be atomized before it is burned. This is accomplished by passing it through burner nozzles en route to the incinerator. The burner nozzles are usually designed to accommodate specific wastes. Liquid-injection incinerators have been used for the destruction of polychlorinated biphenols (PCBs), solvents, still bottoms, reactor bottoms, motor and industrial oils, lacquers, chemical warfare agents, polymer wastes, and pesticides (EPA 1985a). Wastes with a high content of heavy metals or other inorganics are not suitable for liquid-injection incinerators; neither are wastes high in materials that can clog the nozzles or wastes prone to violent decomposition (e.g., gasoline, peroxides, and explosive wastes) unless the undesired characteristic can be modified by pretreatment (e.g., blending or precipitation of the heavy metals). A supplemental fuel is sometimes needed to ensure complete combustion, particularly for the highly aqueous wastes sometimes encountered at ground-water cleanup sites. About 219 liquid injection incinerators are in service in the United States.

Rotary-kiln incinerators are designed to handle a wide variety of wastes separately and in combination without any pretreatment, including gases, liquids, and solids. They have been used to destroy PCB's, tars, munitions, chemical warfare agents, polyvinyl chloride wastes, and solvent reclamation bottoms (EPA 1985a). It is the method of choice for thermal destruction of mixed (solid and liquid) wastes. About 42 rotary kiln incinerators are currently in service. The EPA has developed a mobile rotary kiln for destruction of PCBs.

Multiple-hearth incinerators are widely used for the destruction of municipal sewage sludge and coal wastes. Although these incinerators can be used for all forms of wastes, including solids, tars, sludges, liquids, and gases, they are best suited for sludges. Pretreatment of some wastes may be necessary before incineration. Wastes containing large amounts of ash create material-handling problems due to the formation of slag. These incinerators also do not provide a preferred alternative for wastes requiring very high temperatures or significant amounts of supplemental fuel. They can, however, handle wastes that need to be evaporated.

Fluidized-bed incinerators can be used for thermal destruction liquid, solid, and gaseous combustible wastes; however, they are commonly used for slurries and sludges such as wastes from oil refineries and pulp and paper mills. Some wastes must be dried, shredded, or sorted before incineration. These incinerators are suitable for wastes high in moisture or ash. Only about nine fluidized-bed incinerators are currently being used to destroy wastes; thus availability is limited by both geographical proximity and waste suitability.

5.2.5.3 Design and Construction Considerations

Thermal destruction of hazardous wastes is a complex technology that requires skillful operators, and experience is required for selection of a system. Waste storage, mixing, and pumping equipment is often needed, particularly for liquid-injection incineration, which requires a homogeneous waste and steady flow. Air pollution by particulates, NO_x, SO_2, and other products must be controlled. Afterburners are often used to destroy organic byproducts. Ash disposal is also necessary.

Mobile units may be the most practical where sites are remote from stationary incinerators or when wastes are particularly toxic or difficult to handle or transport. Some thermal destruction technologies may require testing on a lab- and field-scale prior to their full-scale application.

5.2.5.4 Costs

Thermal destruction costs vary with the waste type and volume; some estimated costs are presented in Table 5-6.

Table 5-6. Approximate Costs for Hazardous Waste Incineration

Type of Waste	Cost ($/ton*)
Drummed	130 to 425
Liquids	55 to 425†
Relatively clean liquids with high Btu value	14 to 56†
Solids and/or highly toxic liquids	420 to 842

* 1986 dollars.
† Some cement kilns and light manufacturers pay for these relatively clean, high-energy-value wastes.

5.2.6 Aqueous Waste Treatment

5.2.6.1 General Description

Aqueous waste streams resulting from cleanup of leaking USTs may require treatment. These include waste plumes from the tank, recovered tank contents or tank residue, ground water or surface water contaminated by the leak, or water contaminated by tank or other equipment cleanup. Treatment technologies vary with the waste type, volume, and concentration. Aqueous waste treatment technologies include the following:

- Air Stripping
- Carbon Adsorption
- Biological Treatment (Aerobic or Anaerobic)
- Precipitation/Flocculation/Sedimentation
- Dissolved Air Flotation
- Granular Media Filtration
- Ion Exchange/Resin Adsorption
- Oxidation/Reduction
- Neutralization
- Steam Stripping
- Reverse Osmosis
- Sludge Dewatering

Detailed discussions of each are presented in Subsection 5.7 (Ground-Water Treatment).

Aqueous waste treatment can be conducted on site or off site. Onsite alternatives include the use of mobile treatment units or the construction of stationary systems. These are often used for site cleanup. The waste can be fully treated on site and discharged to the ground or to surface water, or it can be partially treated on site and discharged to a municipal wastewater treatment plant. The feasibility of the latter alternative depends on the toxicity and treatability of the waste and the capacity of the wastewater treatment plant to accept the pretreated wastewater. Aqueous waste can also be collected and hauled to an offsite treatment facility. The latter is generally an expensive alternative for aqueous wastes because of their weight and volume.

5.2.6.2 Application/Availability

See Subsection 5.7

5.2.6.3 Design and Construction Considerations

See Subsection 5.7

5.2.6.4 Costs

See Subsection 5.7

5.2.7 Deep-Well Injection

5.2.7.1 General Description

Deep-well injection involved the drilling of a well and the injection of wastes into the well. The wells are dug in geologic formations selected with the purpose of permanent containment of the wastes therein. The wastes are injected under pressure to displace native fluids. The volume and porosity of the geologic strata used for deep wells must be sufficient to accept the wastes, and formations capable of preventing migration of the waste must surround the well.

5.2.7.2 Application/Availability

In addition to having a suitable geology to accept and contain the wastes, areas selected for deep-well injection must also have little seismic activity. Of the 159 deep wells in the United States, 60 percent are in Region VI (Texas, Oklahoma, New Mexico, and Louisiana); availability is thus limited.

Only liquid wastes can be disposed of by deep-well injection. Wastes that are viscous or high in suspended solids are unsuitable. This disposal method is therefore not recommended for disposing of wastes from leaking underground storage tanks because the wastes are often mixed with soil. Contaminated ground water or surface water, liquids recovered from a leaking tank, or wastes recovered in liquid form with little soil, however, may be amenable to deep well injection. Suitable waste types include dilute and concentrated acids or bases, heavy metal solutions, inorganic solutions, chlorinated hydrocarbons, solvents, and high Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD) organic solutions.

5.2.7.3 Design and Construction Considerations

Deep wells are limited to specific geological formations. Deep wells used for hazardous waste disposal generally range in depth from a few hundred to a few thousand feet. Figure 5-5 shows a diagram of a typically constructed well.

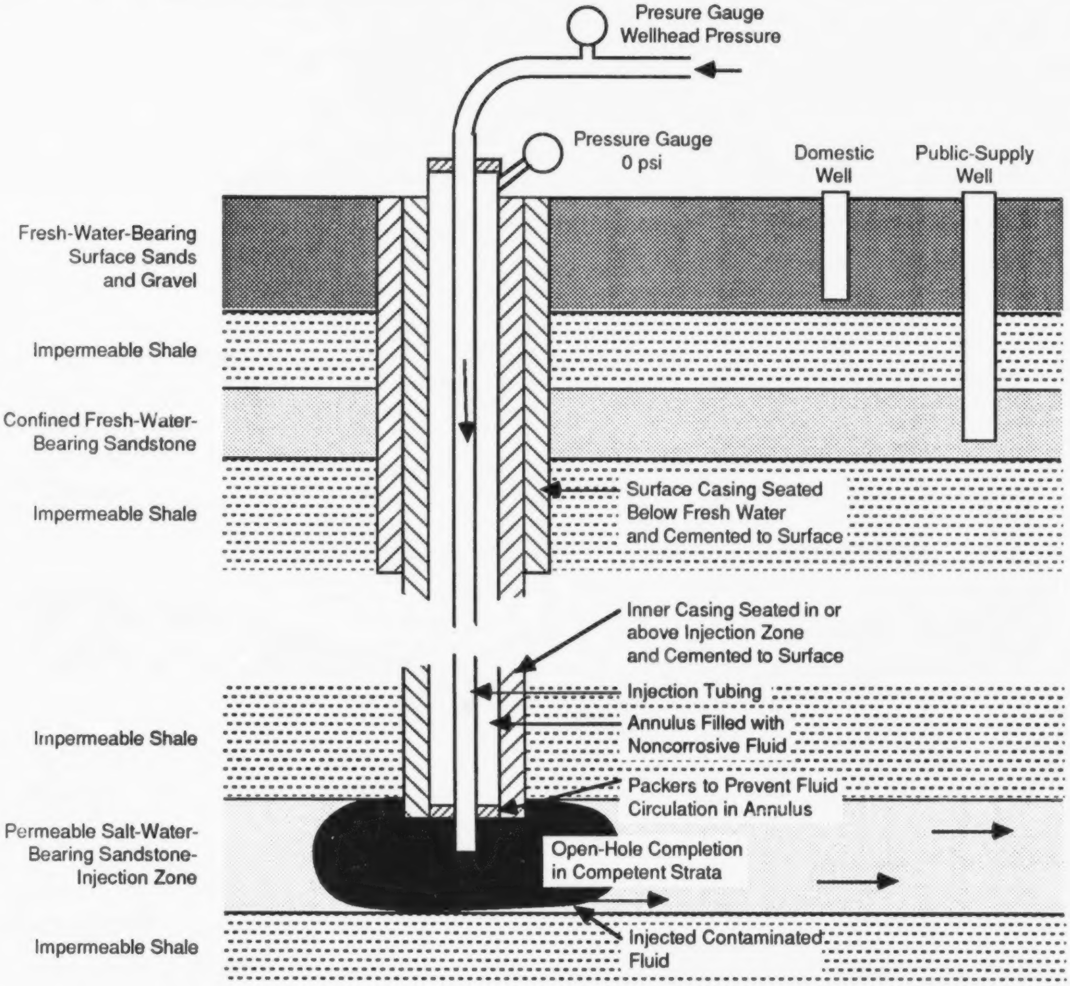
5.2.7.4 Costs

Approximate costs for deep-well injection of oily wastewater (in 1986 dollars) are $0.06 to $0.16/gal or $17 or $43/ton. Approximate costs for toxic rinse water are $0.05 to $1/gal or $141 to $281/ton.

5.3 Free Product Recovery

Sometimes the material released from a leaking UST can be recovered. This is especially true when gasoline and petroleum products are involved. The success of any recovery effort hinges on the hydrogeology of the site, the properties of the material involved, and the quantity released. Technologies

Figure 5-5. Diagram of a conventional industrial injection well completed in sandstone (EPA 1985a).


Presure Gauge
Wellhead Pressure
Pressure Gauge
0 psi
Domestic Well
Public-Supply Well
Fresh-Water-Bearing Surface Sands and Gravel
Impermeable Shale
Confined Fresh-Water-Bearing Sandstone
Impermeable Shale
Surface Casing Seated Below Fresh Water and Cemented to Surface
Inner Casing Seated in or above Injection Zone and Cemented to Surface
Injection Tubing
Impermeable Shale
Annulus Filled with Noncorrosive Fluid
Packers to Prevent Fluid Circulation in Annulus
Permeable Salt-Water-Bearing Sandstone-Injection Zone
Open-Hole Completion in Competent Strata
Impermeable Shale
Injected Contaminated Fluid

applicable to the recovery of materials released from USTs are discussed here.

5.3.1 Dual-Pump Systems

5.3.1.1 General Description

Dual-pump systems can be used successfully when the leaked material floats on the water table. In these systems, one pump draws down the water table and creates a cone of depression into which the free-floating material flows. A second pump transfers the free product to the surface for recovery (Figure 5-6).

5.3.1.2 Application/Availability

Dual-pump recovery systems have been applied in numerous free-product incidents. This arrangement reduces or eliminates the volume of water that must be separated from the product and permits pumping of uncontaminated ground water to a point of free discharge (API 1980).

Dual-pump systems are readily available and their success depends primarily on the plume definition and the hydrogeology of the leak site.

5.3.1.3 Design and Construction Considerations (API 1980)

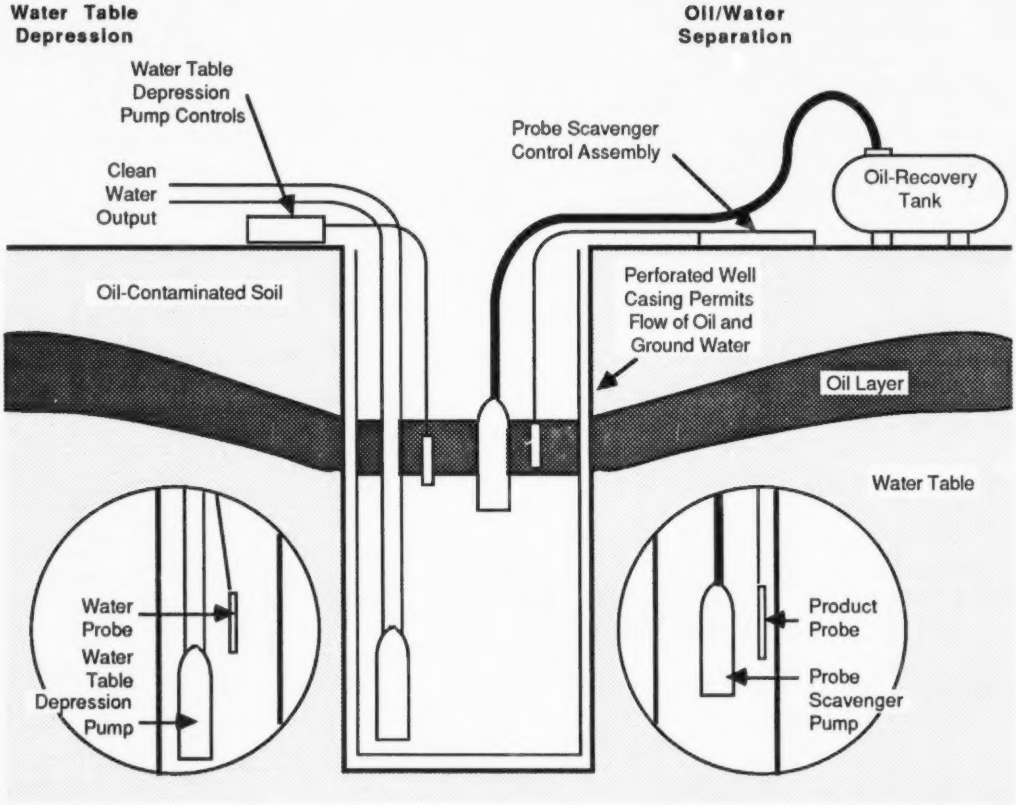
The objective of the drawdown well is to establish a depression in the water table that prevents the oil from spreading and concentrates it for removal. The rate at which fluid is withdrawn and the permeability of the soil determine the size and rate of development of the depression.

Because permeability varies, the depression-forming process differs in each area. When enough information is known about an aquifer, the behavior of the depression cone some distance from the well can be calculated quite accurately. Within 100 to 200 feet of the well, however, such calculations are unreliable because of local characteristics of the aquifer.

The flow rates of the pumps used should meet the maximum gallons per minute expected to be required to establish the depression cone for the desired product recovery rate. Flow rates can be reduced by valve controls, if necessary.

When ordering pumping equipment, the supplier should be informed of its proposed use so that the

Figure 5-6. Dual-pump recovery system (Oil Recovery Systems, Inc., undated).


Water Table Depression
Oil/Water Separation
Water Table Depression Pump Controls
Probe Scavenger Control Assembly
Clean Water Output
Oil-Recovery Tank
Oil-Contaminated Soil
Perforated Well Casing Permits Flow of Oil and Ground Water
Oil Layer
Water Table
Water Probe
Water Table Depression Pump
Product Probe
Probe Scavenger Pump

proper seals, impellers, gears, etc., are provided. Most fractional horsepower pumping equipment has plastic, fiber, or metal impellers and gears, which may not be compatible with certain hydrocarbons.

When positive-displacement suction pumps are used, protective screening or a filter ahead of the pump is needed to protect the pump from dirt or debris. High-speed rotary pumps should be avoided when combinations of oil and water are to be pumped because such pumps encourage formation of oil-water emulsions, which are difficult to separate.

When recovery operations are expected to be extensive, an automated system should be designed and installed. Automated systems will reduce the number of man-hours required to operate and monitor the recovery operation. They also can maintain the continuous depression cone necessary to contain and recover the product.

Precautions should be taken in the design and installation of recovery systems to eliminate the risk of explosive vapors in the area of pumping operations. One technique is to keep the pump unit submerged in liquid at all times. The electrical cable for pumps and automated float control systems must be made of materials that are unaffected by the liquids or vapors that will be encountered. All cables connecting the pumps and the power source should be continuous (no intermediate connections). The power source connection should be at least 5 feet from the well opening.

Electrical pumps or gasoline-powered engines should not be used within 5 feet of the recovery well opening unless they are classified as explosion-proof for Class I, Division I, Group D, use in accordance with NFPA-30. Suction pumps used on volatile products from test or recovery wells should be explosion-proof regardless of their distance from the well.

Depending on the extent of the spill, pumping may be required for an extended period of time. Ideally, pumping should continue through several fluctuations of the water table and should be abandoned only after the mobile product has been reduced to an acceptable level.

Casing is necessary in recovery wells. Any steel, polyvinyl chloride (PVC), or other strong pipe or tubular product may be used. The use of PVC pipe is usually recommended, as it is readily available, light, easy to handle, relatively inexpensive, and available in diameters of 1 to 18 inches. This pipe can be purchased factory-slotted (known commercially as "well screen"), or perforations may be cut in the field. Acrylonitrile-butadiene-styrene (ABS) pipe should not be used, as it tends to become brittle with weathering and dissolves upon contact with petroleum hydrocarbons.

Proper installation of a recovery well is critical to its success. It should be large enough in diameter to accommodate the pumps and controls designed for recovery operations and extend to a depth below the water table. The depth will depend on the aquifer and soil characteristics, the area of contamination, and the area of the cone of depression. To eliminate expenditures for wells or equipment that may be unnecessary or may not perform as planned, recovery well design should be left to professionals.

5.3.1.4 Costs (EPA 1985a)

Some of the factors that determine recovery well costs are the geology, the characteristics of the contaminated and naturally occurring ground water, the extent of contamination, the duration of pumping periods, local wage rates, the availability of supplies and equipment, and the electrical power required. Costs associated with a well system can be categorized as mobilization costs, installation and removal costs, and operation and maintenance costs. Because of these variables, the cost of well installation can vary considerably from site to site. For an accurate estimate of the costs associated with the installation of a well system, as much information as is available should be obtained and evaluated prior to system design.

Removal costs probably will be incurred at all sites at some point when pumping is no longer required. These costs can be offset somewhat by the salvage value of the removed equipment.

The cost ranges for well pumps and screens presented in Table 5-7 give some indication of the cost of recovery wells.

Table 5-7. Product Recovery Costs*

Item	Description	Cost Range ($)
Submersible pumps		
4-inch pump	Pumping depths: 900 ft Horsepowers: 1/3 to 3 hp Capacities: 50 to 2000 gph	435 to 1540
Control boxes		75 to 155
Magnetic starters		165 to 260
Check valves		15 to 430
Well seals		20 to 125
Well screens	Stainless steel, 1 1/4- to 36-inch diameter	34 to 555/ft
	Low-carbon steel, 1 1/4- to 36-inch diameter	18 to 161/ft
	PVC plastic, 1 1/4- to 12-inch diameter	10 to 62/ft

* Data from EPA 1985a.

5.3.2 Floating-Filter Pumps

5.3.2.1 General Description

Floating-filter pump systems are a variation of dual-pump systems. Dual-pump systems utilize two pumps (one located well below the water table to form a cone of depression and a contaminant recovery pump floating on the water surface). In floating-filter systems, the contaminant recovery pump is replaced with a floating filter which acts as the intake for a suction pump located at ground level (Figure 5-7). The floating-filter system has a product-recovery pump with a moving inlet that is free to follow the level of product floating in the cone of depression. The inlet is on a buoy with an oil/water filter built into it. A water-level probe, which controls the ground-water level depression pump, is the only water-level control required.

5.3.2.2 Application/Availability

Floating-filter pumps are used to recover floating contaminants from ground water. They are widely commercially available.

5.3.2.3 Design and Construction Considerations

Design and construction considerations for floating-filter pump systems are the same as those for dual-pump systems; however, larger well casings are required to accommodate the size of the floating filter.

5.3.2.4 Costs

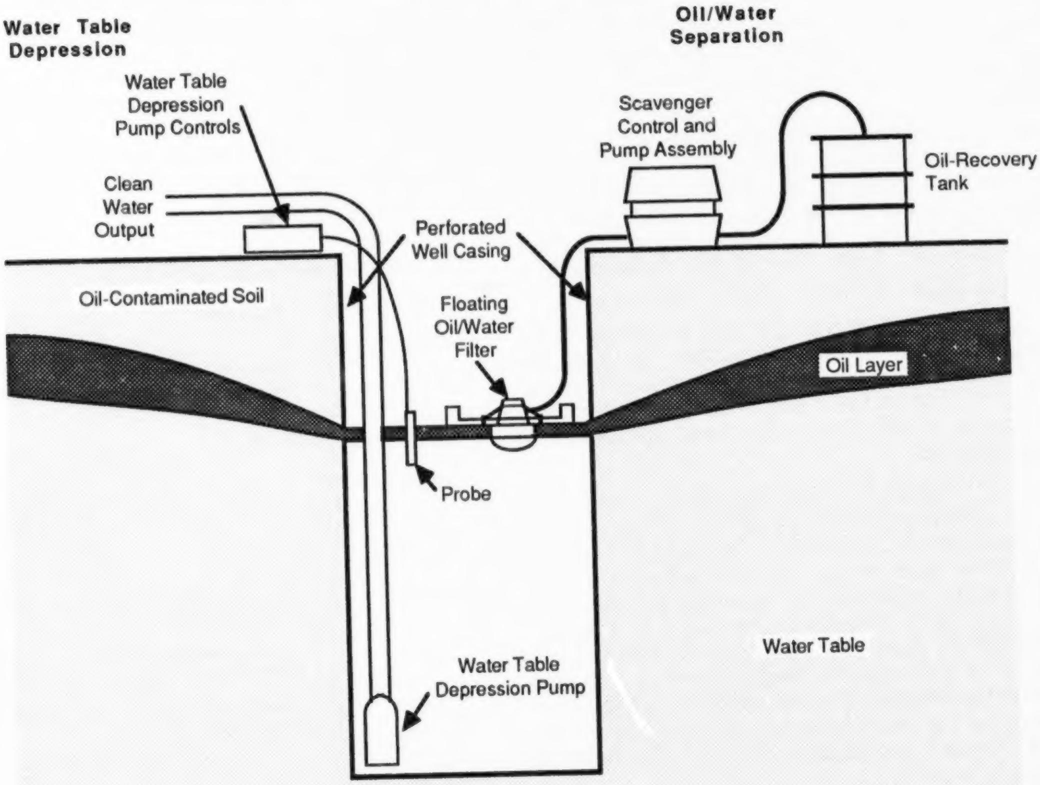
Costs of floating-filter pump systems are comparable to those of dual-pump systems.

5.3.3 Surface Oil/Water Separators

5.3.3.1 General Description

Leaked material brought to the surface will be mixed with water and must be separated. Simple gravity separators are used for this purpose, and this is usually the first step in an above-ground product-recovery process. Further purification of recovered product is normally done offsite.

Figure 5-7. Floating-filter recovery system (Oil Recovery Systems, Inc., undated).


Water Table Depression
Oil/Water Separation
Water Table Depression Pump Controls
Scavenger Control and Pump Assembly
Oil-Recovery Tank
Clean Water Output
Perforated Well Casing
Oil-Contaminated Soil
Floating Oil/Water Filter
Oil Layer
Probe
Water Table
Water Table Depression Pump

5.3.3.2 Application/Availability

Gravity separators are simple pieces of equipment that provide a space where a water/product mixture can separate naturally by gravity. This equipment can be purchased from suppliers or can be field-fabricated.

The efficiency of these separators is a function of the difference in densities between the leaked material and the solubility of the material in water. The larger the density difference and the less water soluble the material is, the better and quicker the separation will be.

5.3.3.3 Design and Construction Considerations

A typical oil/water separator is shown graphically in Figure 5-8. Although designs vary, they all will have the amenities shown here, e.g., siphon break, vent, drain spigots.

If necessary, some simple bench-scale tests can be run to determine separability of the recovered product/water mixture. The separation tank can then be sized from tests that measure settling time for a given volume based on the flow rate for the mixture coming from the recovery well. Separators should be sized to accommodate the maximum flow rate expected.

Once the product has been separated, a means of removing it and the water from the separator will be required. The recovered product can be drummed or pumped into tank trucks and moved offsite for further processing. The water also will have to be disposed of, and it may require further processing before it can be used or returned to the well.

5.3.3.4 Costs

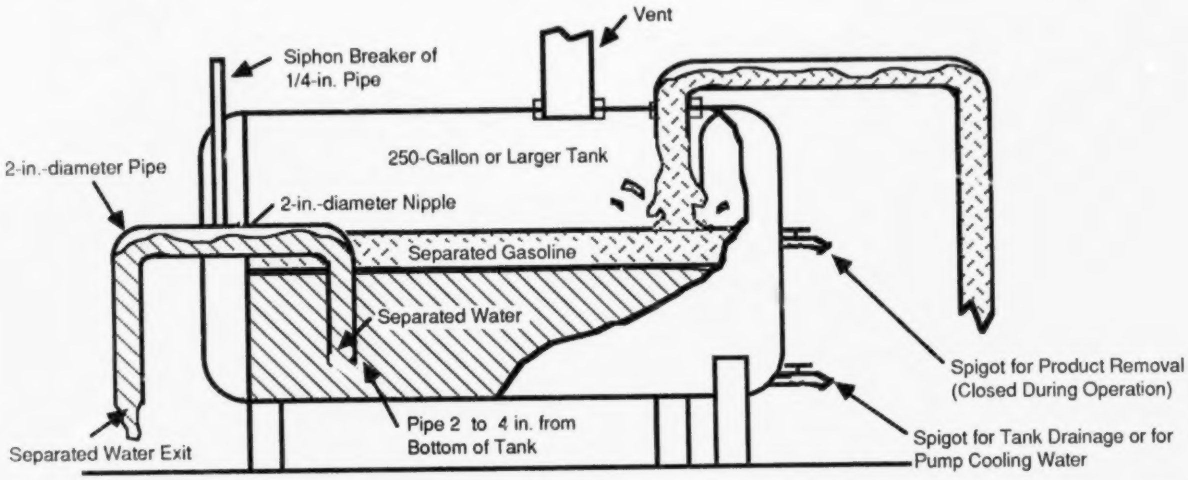
Oil/water separators are available on the market in various sizes and materials of construction. Simple field-fabricated units, which cost a few hundred dollars, represent one extreme. Elaborate coalescing plate separators, which can cost up to several hundred thousand dollars represent the other extreme (Environmental Law Institute 1985).

5.4 Ground-Water Recovery Systems

Control of ground-water contamination involves one of four options: 1) containment of a plume; 2) removal of a plume after measures have been taken to halt the source of contamination; 3) diversion of ground water to prevent clean ground water from flowing through a source of contamination or to prevent contaminated ground water from contacting a drinking water supply; or 4) preventing a product or substance from contacting the formation by lowering the water table beneath a source of contamination. Each of these options is appropriate for initial response and permanent corrective actions for remediation of contaminated ground water.

Technologies for controlling ground-water contamination problems generally fall into one of four categories: 1) ground-water pumping, which involves extraction of water from or injection of water into wells to capture a plume or alter the direction of ground-water movement; 2) subsurface drains, which consist of gravity collection systems designed to intercept ground water; 3) low-permeability barriers, which consist of a vertical wall of low-permeability materials constructed underground to divert ground-water flow or to minimize leachate generation and plume move-

Figure 5-8. Oil/water separator (API 1980).


Vent
Siphon Breaker of 1/4-in. Pipe
250-Gallon or Larger Tank
2-in.-diameter Pipe
2-in.-diameter Nipple
Separated Gasoline
Separated Water
Spigot for Product Removal (Closed During Operation)
Separated Water Exit
Pipe 2 to 4 in. from Bottom of Tank
Spigot for Tank Drainage or for Pump Cooling Water

ment (see Subsection 5.5); or 4) in situ treatment methods for biological or chemical removal or attenuation of contaminants in the subsurface (see Subsections 5.6 and 5.7). These technologies can be used singularly or in combination to control ground-water contamination. Pumping and subsurface drains (EPA 1985a) are addressed here.

5.4.1 Ground-water Pumping

5.4.1.1 General Description

Ground-water pumping techniques involve the manipulation and management of ground water to contain or remove a plume or to adjust ground-water levels to prevent formation of a plume. Types of wells used in management of contaminated ground water include wellpoints, suction wells, ejector wells, and deep wells. The selection of the appropriate well type depends upon the depth of contamination and the hydrologic and geologic characteristics of the aquifer (JRB 1985).

5.4.1.2 Application/Availability

Well systems are versatile and can be used to contain, remove, divert, or prevent development of plumes under various site conditions. The hydrogeologic conditions of a site are the primary controlling feature of a ground-water recovery system.

Pumping is most effective at sites where underlying aquifers have high intergranular hydraulic conductivity. Pumping has been effective at sites where hydraulic conductivities are moderate and contaminant movement is occurring along fractured or jointed bedrock. In fractured bedrock, the fracture patterns must be traced in detail to ensure proper well placement (EPA 1985a). The effectiveness of pumping can be limited in the highly populated residential and commercial zones typical of the locales of the corner gas stations, as pumping may influence other contaminant sources or nearby water supply wells.

Where plume containment or removal is the objective, either extraction wells or a combination of extraction and injection wells can be used. Figure 5-9 depicts the use of a line of extraction wells to halt the advance of the leading edge of a contaminant plume and thereby prevent contamination of a drinking water supply. Use of extraction wells alone is best suited to situations where contaminants are miscible and move readily with water, where the hydraulic gradient is steep and hydraulic conductivity is high, and where quick removal is not necessary. Extraction wells are frequently used in combination with ground-water barrier technologies to prevent ground water from overtopping the barriers, to minimize contaminant contact with the wall, and to reduce the volumes to be pumped.

A combination of extraction and injection wells is frequently used for plume containment or removal. Use of this technique, however, is limited to hydraulic gradients that are relatively flat and hydraulic conductivities that are moderate. The function of the injection well is to direct contaminants to the extraction wells. This method has been used with some success for plumes that were not miscible with water. Figure 5-10 illustrates an extraction/injection well system. One problem with such an arrangement of wells is that windows (i.e., areas where water movement is very slow or nonexistent) can occur. The size of the dead spot is directly related to the amount of overlap between adjacent radii of influence; the greater the overlaps, the smaller the dead spots will be. Another problem is that injection wells can suffer from many

Figure 5-9. Containment by the use of extraction wells (JRB Associates 1985).

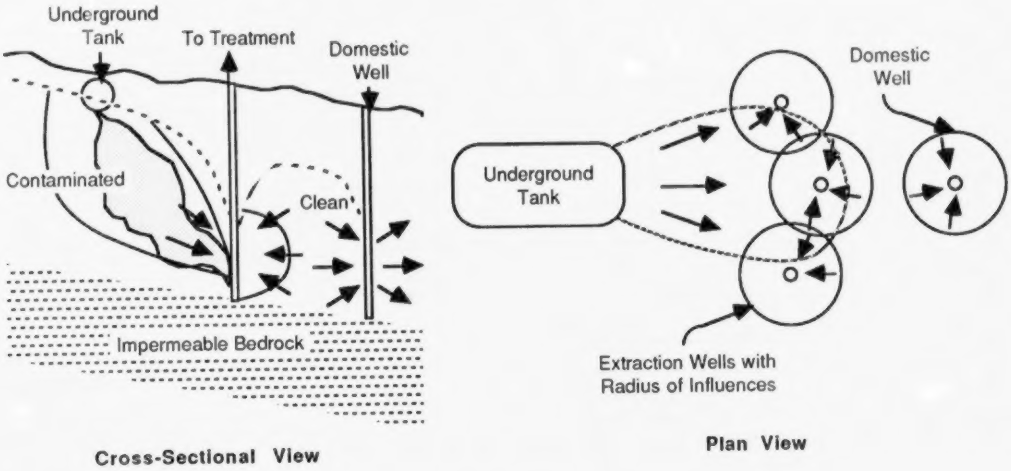
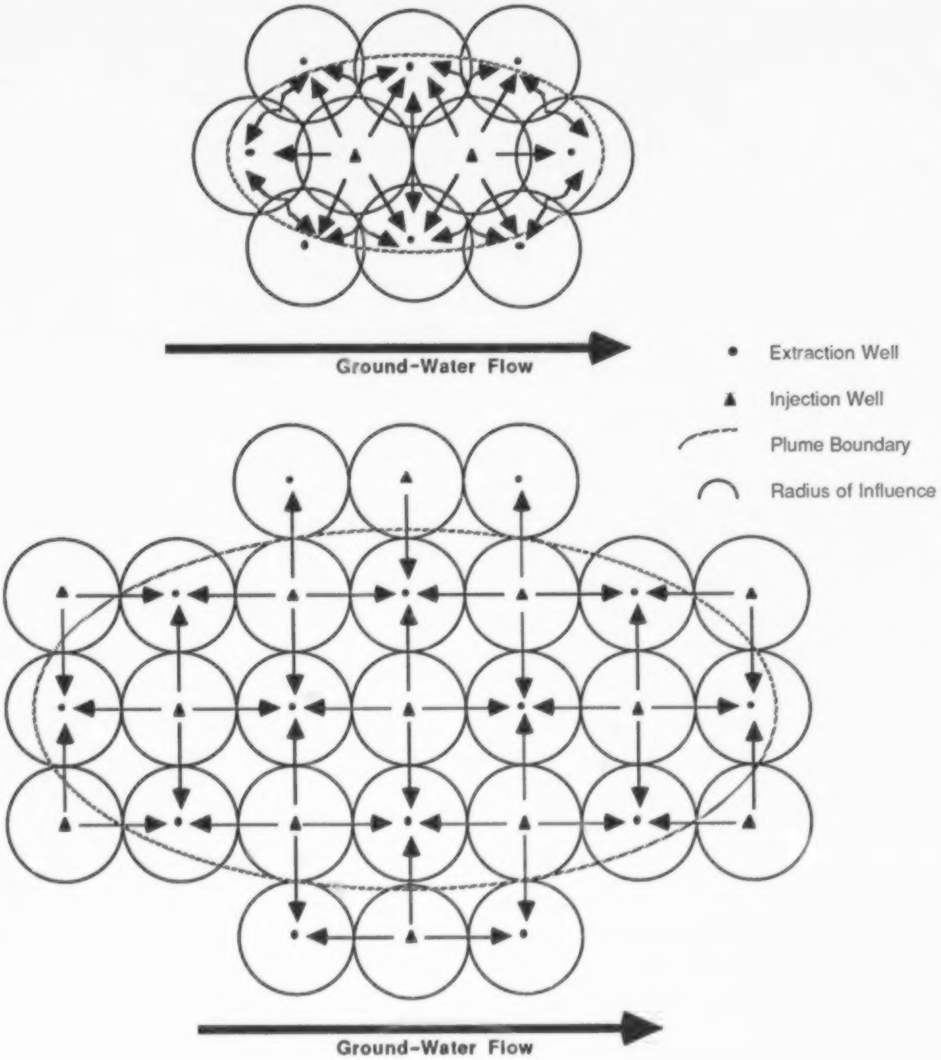


Figure 5-10. **Extraction and Injection well patterns for plume removal (JRB Associates 1985).**

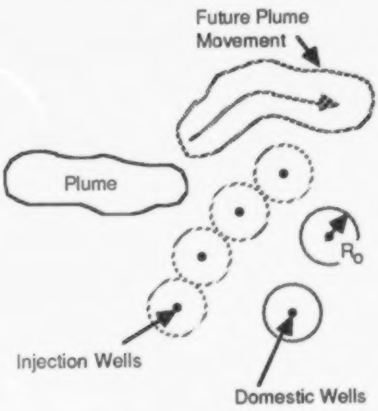


operational problems, including air locks and the need for frequent maintenance and rehabilitation (EPA 1985a).

Extraction or injection wells are also suitable for adjusting ground-water levels, although they are not widely used for this purpose. Plume development can be controlled at sites where the water table intercepts the contaminant source by lowering the water table with extraction wells. For this pumping technique to be completely effective, infiltration must be reduced and free liquids must be removed. Unless these conditions are achieved, the potential exists for development of a plume of contaminants. The major drawback to using well systems for lowering water tables is the costs associated with continuing maintenance of the system (EPA 1985a).

Injection wells can be used to create ground-water barriers that change both the direction of a plume and the speed of plume migration. Figure 5-11 shows an example of plume diversion accomplished by installing a line of injection wells to protect domestic water sources. Creating an area with a higher hydraulic head can force the plume to change direction. This may be a desirable technique for use during initial response, when short-term diversions are needed or when diversion will provide the plume with sufficient time to degrade naturally so that containment and removal are not required (EPA 1985a).

Figure 5-11. **Plume diversion using injection wells (JRB Associates).**



Each of the well types used in ground-water pumping have their own specific applications and limitations. Table 5-8 summarizes the site conditions for which each is most applicable. The components of these well types are described later in this section.

Wellpoint systems are effective in almost any hydraulic situation, but they are best suited for shallow aquifers where extraction is not needed below more than about 22 feet. Beyond this depth, suction lifting (the standard pumping technique for wellpoints) is ineffective. Suction wells operate in a similar fashion to wellpoints and are also limited by depth. The only advantage of suction wells over wellpoints is their higher capacities. During the operation of suction lift wells, it may be necessary to treat air released from the vacuum pumps. Under negative pressure, volatile organics are often released to the air. For extraction depths greater than 20 feet, deep wells and ejector wells are used. Deep well systems are better suited to homogeneous aquifers with high hydraulic conductivities and in situations where large volumes of water must be pumped. Ejector wells perform better than deep wells in heterogeneous aquifers with low hydraulic conductivities. A problem with ejector systems is that they are inefficient and are sensitive to constituents in the ground water that may cause chemical precipitates and well clogging (Powers 1981).

5.4.1.3 Design and Construction Considerations

Several factors must be considered in the design of a pumping well system. These include the hydrogeologic setting, the objective of the well system, and expected installation difficulties. The flow associated with ground-water pumping is not addressed herein; however, such information is available from sources listed in the References and Bibliography. The extraction of water from wells can be for removal of contaminated ground water, control of ground-water (plume) flow, or both. The discharge from wells that are to be used to extract contaminated ground water

Table 5-8. **Criteria for Well Selection***

Parameters	Wellpoints	Suction Wells	Ejector Wells	Deep Wells
Hydrology				
Low hydraulic conductivities (e.g., silty or clayey sands)	Good	Poor	Good	Fair to poor
High hydraulic conductivities (e.g., clean sands and gravel)	Good	Poor	Poor	Good
Heterogeneous materials (e.g., stratified soils)	Good	Poor	Good	Fair to poor
Proximate recharge	Good	Poor	Good to fair	Poor
Remote recharge	Good	Good	Good	Good
Depth of well	Shallow (<20 ft)	Shallow (<20 ft)	Deep (>20 ft)	Deep (>20 ft)
Normal spacing	5 to 10 ft	20 to 40 ft	10 to 20 ft	>50 ft
Normal range of capacity (per unit)	0.1 to 25 gpm	50 to 400 gpm	0.1 to 40 gpm	25 to 3000 gpm
Efficiency	Good	Good	Poor	Fair

* Data from Powers 1981.

must be directed to some treatment facility. Water removed from wells used for ground-water control can be discharged remotely or used locally to enhance the ground-water control system. Treated contaminated ground water also can be used as recharge water to control ground-water flow.

A complete hydrogeological understanding of the site should be established prior to the design of a well system. The design must address the following items: the number and type of wells needed, their pattern, and their spacing; the radius of influence of the wells; the required pumping rates; and whether equilibrium or nonequilibrium pumping will be used.

Determination of the proper spacing of wells for complete capture of a ground-water plume is probably the most important item in system design. Field practitioners have long had a standing "rule of thumb" for estimating well spacing: adjacent cones of depression should overlap (i.e., radii of influence should overlap). This method is reasonably accurate for aquifers that have low natural flow velocities, but it will not be valid for aquifers with high natural flow velocities.

Determining the radius of influence for a well in a given aquifer is critical in corrective-action design because it affects well spacing, pumping rates, pumping cycles, and screen lengths. The radius of influence of a well increases as pumping continues until equilibrium conditions are reached (i.e., when aquifer recharge equals the pumping rate or the discharge rate).

The most accurate method for estimating the radius of influence is by pumping test analysis. Pumping tests can identify recharge boundaries, barrier boundaries, and slow storage release conditions. The pumping test should be performed until equilibrium conditions are reached. Typical test durations for a confined aquifer are about 24 hours, whereas they may be several days for an unconfined aquifer.

When pumping test data are lacking or incomplete, rough approximations of the radius of influence can be obtained by use of equations and the values of transmissivity or hydraulic conductivity, pumping times, and coefficient of storage. Because these estimates are approximate and do not take recharge into account, the value of R should be adjusted downward so greater overlap of the cones of depression will occur. This lowers the probability that contaminants will escape between the wells.

For a confined aquifer, capacity (and therefore pumping rate) is directly proportional to the drawdown as long as the aquifer is not dewatered. Increasing the pumping rate will not affect the radius of influence, but it will affect how long pumping is necessary. In situations where the contaminated plume floats, drawdowns and pumping rates will probably be small. Large drawdowns and high pumping rates are desirable where contaminants are dispersed throughout the aquifer, quick removal is desired, and natural ground-water flow rates are large.

For an unconfined aquifer, the maximum efficiency for well operation occurs at about 67 percent of the maximum drawdown; pumping rates should be adjusted accordingly.

Equilibrium pumping is used in most plume management systems because it allows greater well spacing, which reduces the number of wells required. It is also easier to design and usually entails lower O&M costs. Nonequilibrium pumping may be a better alternative for aquifers with low hydraulic conductivity, for nonmiscible plumes such as gasoline, and for sites with ground-water barriers or scant recharge.

Once the general approach to the remedial action and the time constraints have been established, the design of the system as a whole can proceed. Optimal system designs may include the integration of many different techniques that involve not only strategies other than ground-water pumping, but combinations of the various ground-water pumping strategies discussed herein. Initial well locations, estimated pumping rates, and desired drawdowns for both extraction and injection wells can be established. The proposed system can be modeled to predict the response of the aquifer, and subsequent system refinements can be made until the system is deemed to be workable. This procedure can be done manually for small systems, or several computer programs are available for this use for both small and large systems.

The following subsections describe the four types of extraction wells typically used in ground-water pumping systems. All extraction wells share the following common components: 1) access to the aquifer, 2) openings that allow ground water to enter the well, and 3) a means of moving the ground water to the surface. Access to the aquifer is by means of a hole from the ground surface to the depth at which the target ground water exists. This hole can be created by pushing materials out of the way of an advancing tool or by drilling a hole and removing geologic materials from the ground ahead of the advancing tool. (These procedures are discussed in greater detail later in this subsection, under Well Installation Methods.)

The hole to the depth of the target ground water is necessary so that ground water can move from the aquifer into the well. Typically, a perforated or slotted section of pipe, known as a well screen, is placed at the bottom of the hole. Well screens can be made of heavy wire mesh, continuous wire wrappings, slotted or drilled pipe, or expanded and rolled sheet-stock.

They can be made of inexpensive plastic and metal materials or of relatively expensive chemically resistant or inert materials. Well screens are usually attached to a solid-walled pipe, known as the well riser, that extends to the surface of the ground and serves to hold the hole open and sometimes to convey the ground water to the surface. If wells are installed in bedrock or where there is little danger of the hole collapsing, the screen and riser pipe are sometimes omitted from the deeper portion of the hole. Other details of pumping wells vary with the particular well type and are discussed in the following subsections.

Suction Lift Wells (Pumping Less Than 22 feet of Lift)

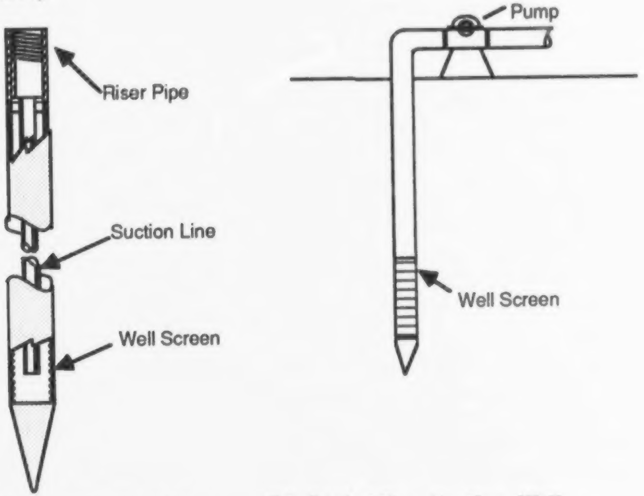
Suction-lift wells can be used to remove ground water that is less than 22 feet below the pump, usually located at or near ground surface. The suction pump reduces the pressure of air (or water) in the pipe above the potentiometric surface of the ground water to a point where atmospheric pressure forces the ground water up to the pump intake, where it is drawn into the pump and expelled through the pump discharge. Special caution must be observed during the pumping of ground water contaminated with high concentrations of volatile or explosive compounds, as the reduced pressure used in the extraction process may produce hazardous conditions. Also, if the reduced pressure is likely to lead to chemical changes in the water and cause precipitation of solids and subsequent clogging of the well screen, other methods may have to be applied.

The suction can be applied either to a pipe with its opening at the bottom of an open-topped well (Figure 5-12a) or directly to the well casing (Figure 5-12b). The first method merely removes the water standing in the well and relies on gravity alone to force water out of the aquifer to refill the well. The second method removes the water standing in the well and uses both gravity and atmospheric air pressure to refill the well, which provides a somewhat higher recovery rate. This enhanced recovery entails greater installation cost, as the well must be airtight and sealed tightly in the ground. As in any suction-type process, the system must remain closed for proper operation. If the water level in an open-topped well drops below the water intake pipe or leaks occur in the well casing, efficiency can drop greatly, maybe even to zero. The same is true if the aquifer water level drops below the top of the well screen in a sealed-top well. Some situations may call for a special well design that includes drawdown protection to prevent loss of suction. These are design considerations that should be considered before the selection of any well system that depends on suction pumping techniques.

Individual Suction Lift Wells. When only a few wells are required or when wells are widely spaced, individual shallow wells with diameters ranging from as small as 1.5 in. to very large ones can be equipped with a suction pump that will lift the desired volume of water from the ground. Wells of this type can typically remove from 5 to 400 gal/min of water from properly designed and constructed wells. Each well must have its own pump, power supply (either an electric motor or a combustion engine), and water discharge.

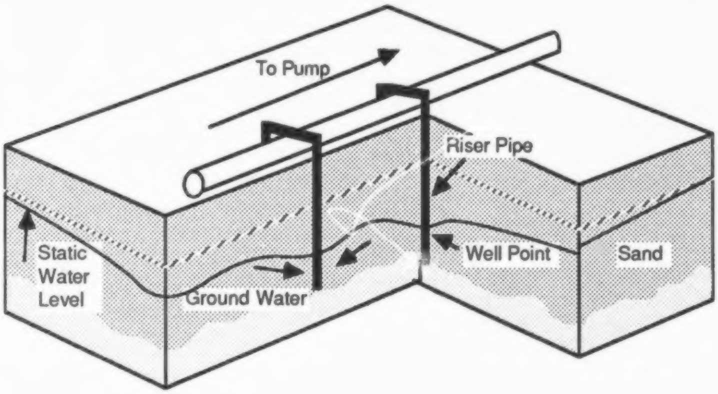
Multiple Suction Lift Wells (Wellpoint Systems). When a large number of relatively closely spaced shallow wells would be advantageous, multiple suction wells can be connected to a common suction pump via a manifold (Figure 5-13). Such systems, commonly referred to as wellpoint systems, have been used

Figure 5-12. Suction wells (Driscoll 1986).



(a) Open-Topped Suction Well **(b) Sealed-Top Suction Well**

Figure 5-13. **Multiple suction lift wells (Well point system) (Driscoll 1986).**



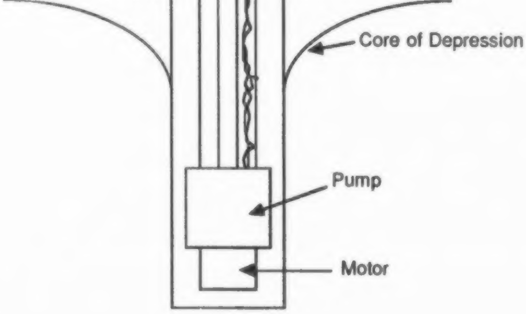
widely in the construction industry to dewater foundation excavations, are readily available, and are adaptable to a multitude of situations and configurations. Valving can be installed in the manifold network to allow controlled production from individual wells and to prevent overpumping and loss of system efficiency. Systems of this type can extract large volumes of ground water, the amounts limited only by the capacity of available pumps and header pipes. Typical systems can extract 25 to 25,000 gal/min.

Deep Wells (Pumping Greater Than 22 feet of Lift)

Ground-water pumping systems that have to lift the water more than about 22 ft must depend on techniques of pumping other than those described in the previous subsection. Because these other techniques work on the principle of increasing the pressure on the water at the bottom of the well, they are known as positive-pressure lifting methods. Devices must be lowered into the wells and powered so as to increase the pressure on the water at the bottom of the well to overcome the gravitational pull on the water and push it up the discharge pipe to the ground surface. Many such devices are available, but relatively few of them fulfill the requirements of ground-water pumping sufficiently to be considered here. The two general types of deep-well pumping discussed here are 1) mechanical pumps lowered to the bottom of the well, and 2) hydraulic pumps that depend on venturi-effect velocity/pressure changes to generate sufficient pressures to lift the ground water to the surface.

Submersible or Downhole Turbine-Pumped Wells. Deep wells having a 4-inch diameter or larger riser pipe can accommodate readily available submersible water pumps (Figure 5-14). These pumps, which are manufactured for the water-supply industry, have the electric motors attached directly to the water pump and require both electricity supply cables and an attached pipe large enough to accommodate pump discharge. They are available in capacities ranging from 5 to well over 1000 gal/min and have working depths ranging from 0 to more than 2000 ft below surface. These pumps depend on water flowing past the motor to cool and protect it from overheating; therefore, care in installation and maintenance of adequate space around the pump are critical. Selection of casing size (riser and screen diameter) must satisfy two requirements: 1) it must be large enough to accommodate the pump and allow enough clearance for efficient operation, and 2) it must ensure proper hydraulic efficiency of the well at the intake section of the pump (Johnson Division, UOP, Inc.

Figure 5-14. **Submersible pump.**



1975). The controlling factor is usually the size of the pump selected for the desired capacity and head. As a good rule of thumb, the casing size should be two standard pipe sizes larger (and not less than one standard pipe size larger) than the nominal diameter of the pump. Submersible pumps are efficient and relatively economical to purchase and operate. One drawback to this type of pump is that the discharge pipe, pump, and motor must be removed from the well to service any portion of the system.

An advantage of downhole turbine (or vertical lineshaft) pumps is that the pumping mechanism can be placed at the bottom of the well while the power unit is kept above ground (Figure 5-15). These pumps are driven by surface-mounted electric motors or combustion engines, which can be easily repaired or replaced in the event of breakdown or failure. The power is delivered to the turbine pump through a driveshaft house within a riser pipe that serves as both pump discharge pipe and driveshaft stabilizer. To achieve discharge capacities equivalent to that from submersible pumps may require slightly larger casing. Vertical lineshaft pumps have been used primarily for large-capacity municipal and industrial production wells with the ability to pump thousands of gallons per minute, which are powered by sources ranging from a few to more than a thousand horsepower and from depths reaching as much as 2000 ft.

Ejector Wells. Ejector wells, or deep-well jets, function on the principle of changing velocities and subsequently changing pressures to produce lifts of up to 125 ft of water in wells that are not subject to being pumped dry. Figure 5-16 demonstrates the basic operating parts of this system as well as its main drawback--poor efficiency. In spite of the poor efficiency (15%), the benefits of this type of pumping system can be great when closely spaced wells with lifts ranging from greater than 22 ft up to 125 ft are required. The advantage of having all moving parts of the system kept above ground is obvious, and as in the case of suction well systems, ejector wells can be operated by a single pump per well, or multiple extraction wells can be driven by a single pump if properly designed distribution manifolds are used.

Figure 5-17 shows two commonly used versions of the ejector well. A closeup view of a two-pipe system is presented in Figure 5-16. The single-pipe system, in which the well riser is part of the pumping system, is shown in Figure 5-18.

Well Installation Methods

Each well type discussed in the preceding subsections can be constructed in a range of capacities and sizes. The selection of appropriate techniques to install an extraction well in a specific setting will depend on the geologic materials present, the depth to

Figure 5-15. Downhole turbine (Driscol 1986).

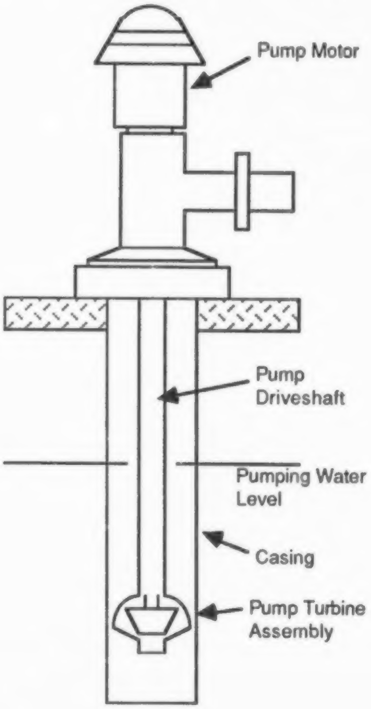


Figure 5-16. Deep well jet pump (Driscol 1986).

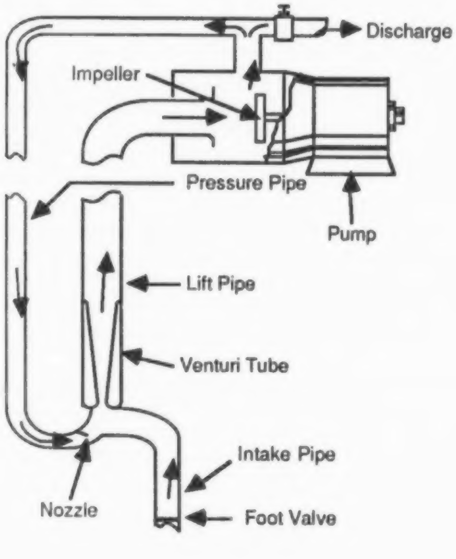


Figure 5-17. Variations of ejector wells (Powers 1981).

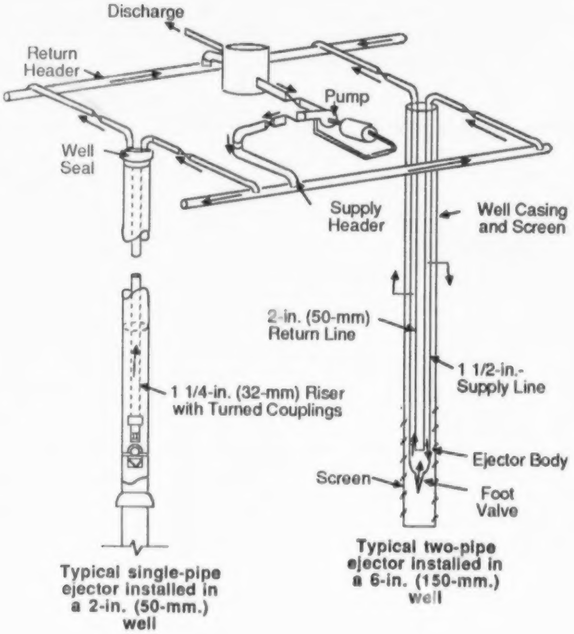
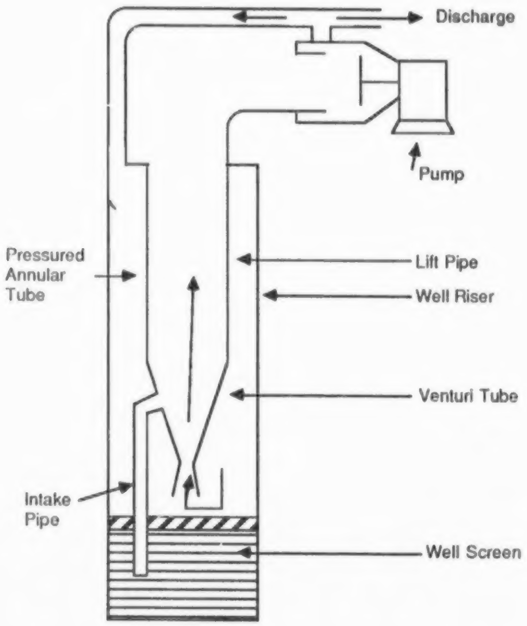
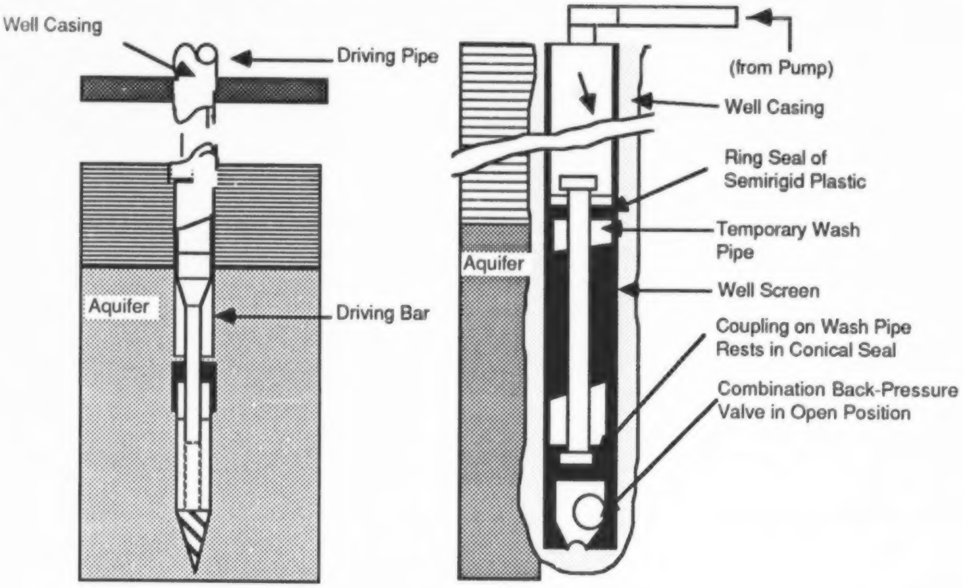

Discharge
Return Header
Pump
Well Seal
Supply Header
Well Casing and Screen
2-in. (50-mm) Return Line
1 1/2-in.- Supply Line
1 1/4-in. (32-mm) Riser with Turned Couplings
Ejector Body
Screen
Foot Valve
Typical single-pipe ejector installed in a 2-in. (50-mm.) well
Typical two-pipe ejector installed in a 6-in. (150-mm.) well

Figure 5-18. Single-pipe ejector.

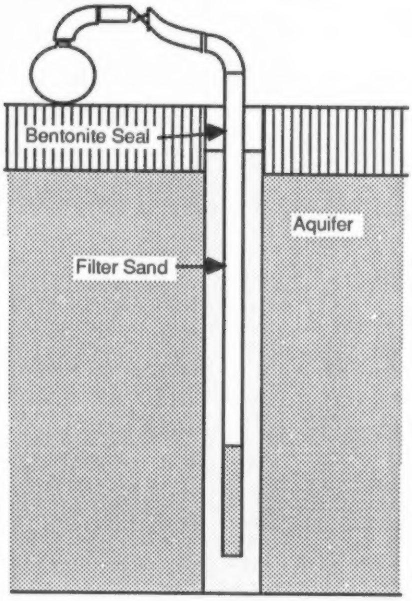

Discharge
Pump
Pressured Annular Tube
Lift Pipe
Well Riser
Venturi Tube
Intake Pipe
Well Screen

the target zone, the desired well type, the required capacity, and other considerations. Three basic well installation techniques (Figure 5-19) are discussed in the following subsections. Table 5-9 summarizes these methods. The selection of the materials of construction dictates which installation techniques can be used. Materials and some installation limitations they present are discussed briefly in a subsequent separate subsection.

Figure 5-19. **Types of wells (Johnson Division, UOP, Inc. 1975; Powers 1981).**


Well Casing
Driving Pipe
Aquifer
Driving Bar
(from Pump)
Well Casing
Ring Seal of Semirigid Plastic
Temporary Wash Pipe
Aquifer
Well Screen
Coupling on Wash Pipe Rests in Conical Seal
Combination Back-Pressure Valve in Open Position

Driven Well **Jetted Well**


Bentonite Seal
Aquifer
Filter Sand

Drilled Well

Table 5-9. Common Methods of Well Installation

Method		Applications/Limitations			
Basic	Variations	Geologic Material	Size Range Diameter	Depth Range	Installation
Driven		Unconsolidated materials free of boulders	1-3 inches	Up to 100 ft	During hole opening
Jetted		Unconsolidated materials free of boulders	Up to 24 inches	Up to 200 ft	During or after hole opening
Drilled	Solid stem auger	Unconsolidated materials without excess boulders	Up to 18 inches	Up to 100 ft	After hole opening
	Hollow stem auger	Unconsolidated materials without excess boulders	Up to 18 inches	Up to 100 ft	During or after hole opening
	Bucket auger	Unconsolidated materials without excess boulders	Up to 72 inches	Up to 100 ft	After hole opening
	Conventional hydraulic (and reverse)	Any type	Up to 72 inches	Unlimited	After hole opening
	Air rotary and reverse	Any type	Up to 72 inches	Unlimited	After hole opening
	Cable tool	Any type	Up to 72 inches	Unlimited	After hole opening

Driven Wells. Driven wells are, in a general sense, pipes driven into the ground by pile-driving hammers. They can be significantly more complex than this simple definition implies, but, on completion, all driven wells consist of a riser pipe to which a screen is attached at the bottom of the well. These wells are usually 1.5 to 3.5 inches in diameter, have a conical tip, and are of a material sturdy enough to withstand the forces of the installation technique. Driven wells are usually pumped by suction or ejector pumping systems. Their installation is usually limited to areas comprising relatively soft, unconsolidated materials; and their maximum depth is approximately 100 ft.

Many suction wellpoint systems use driven wells. In these systems the tight well-to-formation seal often eliminates the need for installing artificial well seals to prevent loss of suction, and the cost of installing driven wells is significantly less compared with other types of wells.

Jetted Wells. Jetted wells rely on fluid pumped through the well riser and screen and its forceful exit from the bottom tip of the well to dislodge unconsolidated geologic materials immediately below the specially designed well tip. The well screen and riser then sink under their own weight, often with the assistance of a drive hammer, which is used to overcome friction along the length of the well pipe.

Jetting wells into place has certain advantages over driving wells. Jetting allows installation of small-diameter wells to greater depths than driving does in the same geologic setting. Also, somewhat larger-diameter wells can be installed, which permits the use of some deep-well pumping systems. In addition, because of the washing action of jetting and removal of fine materials, only minimal well development is necessary to achieve optimal production characteristics in these wells. One major drawback to this installation technique in certain settings is that relatively large volumes of water are required. This may dilute contaminant concentrations and increase the total volume of ground water that ultimately must be extracted from the well. Jetting can also significantly alter ground-water flow patterns in the vicinity of the well during installation.

Drilled Wells. Both driving and jetting wells into place are cost-effective and technically advisable in many settings. In certain hydrogeologic settings, however, neither is advisable. In this case, a well borehole must be constructed in which to install the ground-water extraction well. Wells installed in drilled boreholes can be of nearly any type construction, material, depth, or diameter, and can be designed to produce a specific discharge rate and drawdown to facilitate ground-water control and enhance recovery of contaminated ground water. Ground-water pumping from drilled wells can be accomplished by suction pumps (when lift is less than 22 ft) or by any of the deep-well pumping techniques mentioned previously.

Auger drilling, rotary wash, air rotary, and cable tool are some of the techniques used to drill boreholes for installing wells. Each general drilling technique has its own set of variations, including solid- or hollow-stem augering, normal or reverse circulation in rotary wash and air drilling, and a cased or open borehole during rotary or cable tool drilling. All of the drilling techniques and their variations have advantages and disadvantages when used in specific settings or under given requirements. In some settings, two or more drilling techniques will be used to construct a single borehole.

Wells installed in drilled boreholes can vary from simple screened iron or PVC pipes placed in the hole to multiple-cased stainless steel, PTFE, or PFA well pipe with O-ring joint seals, artificial screen filterpacks, and borehole seals of volume-expanding materials.

Well Construction Materials

Materials used in the construction of wells can be grouped according to the function they serve. Materials should be selected for risers, screens, filler packs, and well sealing materials that minimize corrosion, chemical deterioration, or encrustation. Likewise, the proper material type, wall thickness, and screen slot-size must be selected to withstand the physical stress placed on the well during installation and operation.

Not all wells require all parts but all wells consist of, at a minimum, a riser pipe and a screen, which is usually attached at the bottom. These two components allow physical access to and removal of ground water from the aquifer. They can be constructed of black iron pipe, PVC, or other construction-grade plastic pipe, stainless steel, or fluorocarbon (Teflon) plastics. These pipes are commercially available in standard sizes ranging from 1 to 72 inches. Specially manufactured or machined pipe has threaded ends to allow easy connection of pipe sections, whereas other pipe requires welding, gluing, or some mechanical connection during the installation process.

Artificial screen filter packs are often installed to provide a uniform, controlled-size material surrounding the well inlet. This is often advisable to allow full production capabilities and to eliminate unwanted fine materials from entering the well. Artificial filter packs can consist of sand or gravel poured or pumped into the borehole after the pipe has been placed so that it settles around the well screen, or specially designed bags can be attached to the screen before installation and filled with the desired material. Sometimes the natural geological formation material can be developed by a variety of techniques to produce the desired characteristics. In this case, an artificial filter pack will not be necessary.

It is often desirable for the well screen to be isolated from the geologic formation above it. This is most often accomplished by installing a borehole seal above the screened interval or filter pack. Borehole seals vary in design and material and can include inflatable packers, swelling bentonite clay, cement, concrete, mixture of cement and bentonite or organic polymers, and expanding cements (often used in combinations to achieve the desired result).

5.4.1.4 Costs

Costs of well systems for plume management can vary greatly from site to site. Some of the factors that determine these costs are the geology, the characteristics of the contaminated and naturally occurring ground water, the extent of contamination, the periods and duration of pumping, local wage rates, the availability of supplies and equipment, and the electrical power required. Costs associated with a well system can be categorized as mobilization costs, installation and removal costs, and operation and maintenance costs. Tables 5-10 through 5-12 provide typical costs for well pumping system installation and operations.

The complexity of developing costs for ground-water pumping systems led Geraghty and Miller, Inc., to develop a method for estimating total capital and operating costs for deep wells based on the use of existing hydraulic models (Lundy and Mahan 1982). They have applied the model to a number of scenarios and the resulting cost estimates provide considerable insight into how aquifer characteristics affect cost and how the cost of well system components compares with total capital costs.

Table 5-13 summarizes seven recovery system cost scenarios to which the cost methodology was applied. For these scenarios, the plumes were assumed to be moving in unidirectional flow fields and to have the following dimensions: 250 to 2500 feet wide, 500 to 5000 feet long, and 25 to 250 feet deep.

A high transmissivity (100,000 gal/day/ft) is assigned to four low-flux scenarios. A low transmissivity (5000 gal/day/ft) is assigned to three high-flux scenarios (EPA 1985).

Table 5-10. 1986 Costs for Selected Pumps and Accessories*

Pump/accessory	Description	Cost Range ($)
Jet pumps		
Shallow well	Pumping depths: 25 ft Horsepowers: 1/3 to 1-1/2 hp Capacities: 60 to 27,000 gph	210 to 520
Deep well	Pumping depths: 320 ft Horsepowers: 1/3 to 2 hp Capacities: 60 to 1,000 gph	260 to 680
Jets and valves	Single-pipe jets Double-pipe jets	40 to 105 30 to 80
Seals	Single- or double-pipe seals	15 to 40
Foot valves		10 to 50
Air volume controls		10 to 30
Submersible pumps		
4-inch pump	Pumping depths: 900 ft Horsepowers: 1/3 to 3 hp Capacities: 50 to 2,000 gph	445 to 1,565
Control boxes		80 to 155
Magnetic starters		165 to 260
Check valves		15 to 440
Well seals		20 to 125
Vacuum pumps		
Diesel motors	800 to 7,000 gpm (48,000 to 420,000 gph)	14,000 to 52,000
Electric motors	800 to 7,000 gpm (48,000 to 420,000 gph)	9,000 to 37,000

---

* Data from JRB Associates 1985.

Table 5-11. 1986 Costs for Well Screens and Wellpoints*

Type	Description	Cost range ($)
Driven wellpoints	Stainless steel, 1-1/4 to 2 inches in diameter	35 to 44/ft
	Low carbon steel, 1-1/4 to 2 inches in diameter	16 to 31/ft
	PVC plastic, 1-1/4 to 2 inches in diameter	5 to 6/ft
Well screens	Stainless steel, 1-1/4 to 36 inches in diameter	34 to 555/ft
	Low carbon steel, 1-1/4 to 3 inches in diameter	18 to 161/ft
	PVC plastic, 1-1/4 to 12 inches in diameter	10 to 62/ft
Jetting screens (fittings)	Cast iron or mild steel, 2 to 12 inches in diameter	31 to 277/ft

* Data from Johnson Division, UPO, Inc. 1975.

Table 5-12. 1986 Costs for Completion of 2- to 4-Inch-Diameter Wells*

Drilling Method	Range of Well Completion Costs† ($)
Conventional hydraulic rotary	30 to 50/ft
Reverse circulation hydraulic rotary	40 to 60/ft
Air rotary	30 to 50/ft
Hollow-stem auger	30 to 50/ft
Cable tool	25 to 75/ft
Hole puncher (jetting)‡	30 to 50/ft
Self-jetting or driven‡	20 to 30/ft
Mobilization	200 to 1000/rig

* Data from PEI.

† Includes drilling, well material, and installation costs. Can be significantly higher in some settings and in highly contaminated environments.

‡ Includes rental of all necessary equipment, e.g., wellpoints, pumps, and headers.

Table 5-13. **Summary of seven recovery system cost scenarios.***

Aquifer and plume characteristics		Cost ($1,000)									
		Delineation †	Design †	Wells/drains †	Surface infrastructure †	Treatment facility †	Wells/drains (O&M) ‡	Treatment (O&M) ‡	Monitoring (O&M) ‡	Total Capital Costs	Total O&M
Low flux, high transmissivity (100,000 gal/day/ft) (plume width x length x depth, ft)											
2 wells; 2 gpm	(250 x 500 x 25)	85	29 to 113	16.9	40	34	16.9	5.6	11	203 to 289	34
2 wells; 2 gpm	(250 x 500 x 250)	169	29 to 113	56	40	34	23	5.6	11	329 to 413	40
2 wells; 20 gpm	(2,500 x 5,000 x 25)	226	29 to 113	16.9	169	45	16.9	5.6	11	487 to 572	34
2 wells; 20 gpm	(2,500 x 5000 x 250)	453	29 to 113	68	169	45	23	5.6	11	764 to 849	40
High flux, low transmissivity (5,000 gal/day/ft)											
4 wells; 40 gpm	(250 x 500 x 25)	85	29 to 113	34	40	69	16.9	16.9	11	243 to 328	45
4 wells; 40 gpm	(250 x 500 x 25)	169	29 to 113	124	40	56	23	16.9	11	419 to 503	51
4 wells; 400 gpm	(2,500 x 5,000 x 250)	453	29 to 113	147	169	124	82	88	11	924 to 1007	119

* Data from Lundy and Mahan 1982; costs were updated from 1982 dollars to mid-1986 dollars by using the ENR Construction Cost Indices for 1982 and 1986.

† Capital costs

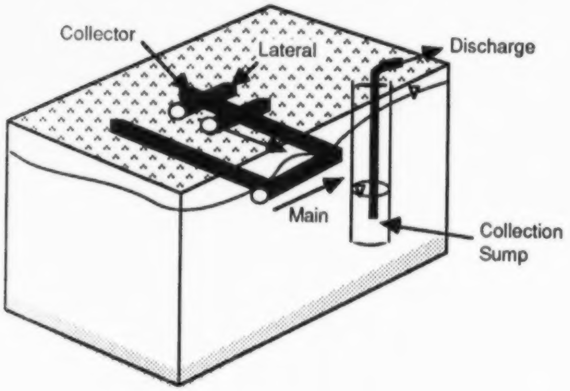
‡ O&M = operation and maintenance costs

5.4.2 Subsurface Drains

5.4.2.1 General Description

Subsurface drains include any type of buried conduit used to convey and collect aqueous discharges by gravity flow. Subsurface drains essentially function as an infinite line of extraction wells. They create a continuous zone of influence in which ground water flows toward the drain. Subsurface drainage components are illustrated in Figure 5-20.

Figure 5-20. Subsurface drainage system components (EPA 1985a).



The following are the major components of a subsurface drainage system:

- Drain pipe or gravel bed--for conveying flow to a storage tank or wet well. Pipe drains are used most frequently at hazardous waste sites. The use of gravel beds or french drains and tile drains is more limited.
- Envelope--for conveying flow from the aquifer to the drain pipe or bed
- Filter--for preventing fine particles from clogging the system, if necessary
- Backfill--to bring the drain to grade and prevent ponding
- Manholes or wet wells--to collect flow and pump the discharge to a treatment plant.

5.4.2.2 Application/Availability

Because drains essentially function like an infinite line of extraction wells, they can perform many of the same functions as wells. For example, they can be used to contain or remove a plume or to lower the ground-water table to prevent water from contacting the released substance. Should a release occur, they also may be installed as a control measure. The decision to use drains or pumping is generally based on a cost-effectiveness analysis. The application of subsurface drains is often greatly restricted for response to gasoline releases at a corner station because of the numerous utilities in the immediate area. Furthermore, the use of an open trench when lighter fraction petroleums and ignitable fluids are present as free product can be dangerous and should be undertaken only with appropriate safety precautions. A variation of subsurface drains (an open trench with a free-product recovery system) is often used, however.

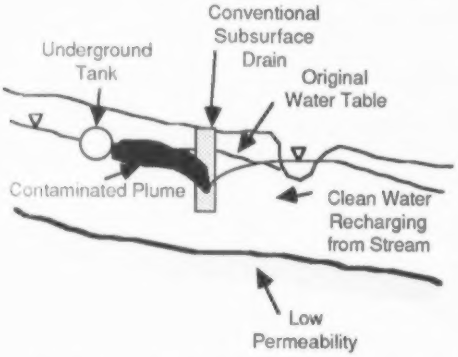
For shallow contamination problems, drains can be more cost-effective than pumping, particularly in strata with low or variable hydraulic conductivity. Under these conditions, a pumping system would be difficult to design and be cost-prohibitive to operate for the maintenance of a continuous hydraulic boundary. Subsurface drains may also be preferred over pumping where ground-water removal is required over a period of several years, as the operation and maintenance costs associated with pumping are substantially higher.

One of the biggest drawbacks to the use of subsurface drains is that they are generally limited to shallow depths. Although it is technically feasible to excavate a trench to almost any depth, the costs of shoring, dewatering, and hard rock excavation can make drains cost-prohibitive at depths greater than 40 feet. In stable, low-permeability soils, however, where little or no rock excavation is required, drains can be cost-effective to depths of 100 feet.

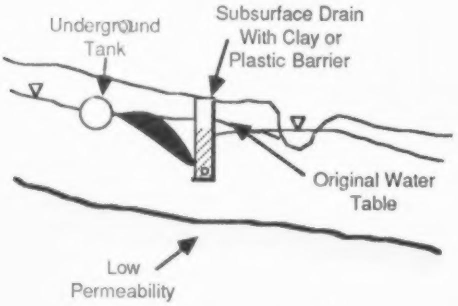
The most widespread use of subsurface drains at UST sites is for the purpose of intercepting a plume hydraulically downgradient from its source (Figure 5-21a). These interceptor drains, as they are commonly called, are frequently used together with a barrier wall (Figure 5-21b) for two reasons. First, when a subsurface drain is to be placed just upgradient of a stream, the drainage system would reverse the flow direction of the stream and cause a prohibitively large volume of clean water to be collected. The addition of a barrier wall would prevent infiltration of clean water from the stream and thus reduce treatment costs. Second, subsurface drains are used in conjunction with ground-water cutoff barriers to prevent the buildup of ground water upgradient of the barrier.

Evaluation of the suitability of subsurface drains as a corrective technology is generally made by comparing the cost-effectiveness of this alternative versus pumping. Subsurface drains can be more difficult and costly to install, particularly if extensive hard rock excavation, subsurface utilities, and dewatering are required. Safety of field workers is also more of a concern with subsurface drains because of the need for extensive trench excavation, potential trench collapse, and gas buildup.

Figure 5-21. **Use of a one-sided subsurface drain for reducing flow from uncontaminated sources (JRB Associates 1985).**



(a) Conventional Subsurface Drain



(b) One-Sided Subsurface Drain.

Drains have several advantages over pumping, however. They are generally more cost-effective in areas with low hydraulic conductivity, particularly when pumping would be required for an extended period of time. They are also easier to operate because water is collected by gravity flow, and they are more reliable because there are no electrical components to fail. When drains fail as a result of clogging, breaks in the pipes, or sinkhole formation, however, rehabilitation can be costly and time-consuming.

5.4.2.3 Design and Construction Considerations

The major elements to consider in designing a subsurface drainage system include:

- Location and spacing of drains to achieve desired head levels.
- Hydraulic design of the conduit, including pipe diameter and gradient.
- Properties and design of the envelope and filter materials.
- Design of a pumping station.

Each of these design elements is discussed in the following subsections.

Location and Spacing of Drains

For design purposes, subsurface drains have been divided into two categories based on their functions: interceptor and relief drains. Interceptor drains are installed perpendicular to ground-water flow and are used to intercept ground water from an upgradient source. These drains are the more commonly applied to abate UST releases. Relief drains are installed parallel to the direction of flow or around the perimeter of a site where the water table is relatively flat. Relief drains are used primarily to lower the water table beneath a site. Figure 5-22 shows how interceptor and relief drains alter the configuration of the water table.

Determining the required location for an interceptor drain is more often based exclusively on the use of field data than on theoretical design. Site investigation data are used to develop potentiometric surface maps, hydraulic conductivity data, plume boundary limits, and geologic cross sections. With these data in hand, the design engineer can pinpoint and stake the design drain line.

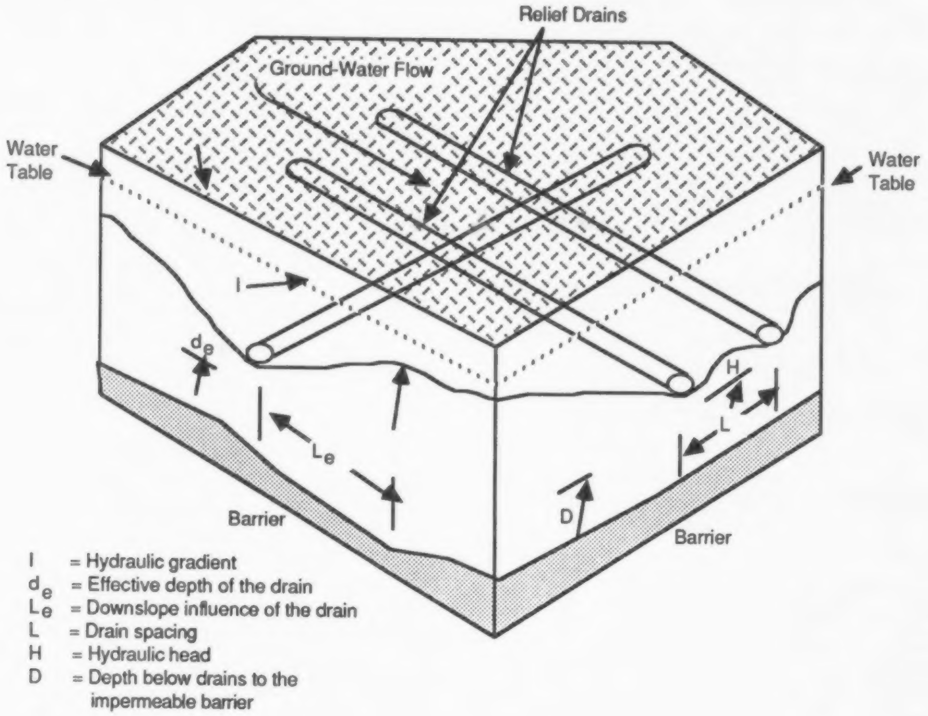
To function properly, an interceptor drain should be installed perpendicular to ground-water flow direction. In stratified soils having greatly different hydraulic conductivities, the drain should rest on a layer of low hydraulic conductivity. If the trench is cut through an impervious stratum, a significant percentage of the product moving laterally could bridge over the drain and continue downgradient. Similarly, if soil layers or pockets with high hydraulic conductivity underly the drain, the substance could flow beneath the drain.

Underflow can be minimized by placing impermeable liner material at the base of the trench before laying a thick (1- to 3-foot) gravel bedding. Where pockets of highly permeable soils are found (e.g., in the scour channel of an alluvial area), a manhole could be constructed at the lowest point of the permeable soil and a small lift station and force main could be installed to carry the ground water from this low area back up to the adjacent gravity flow section of the drainage system (see Figure 5-23). A third solution is to install a barrier wall downgradient of the drain and to key it in to a low-permeability layer.

Filters and Envelopes

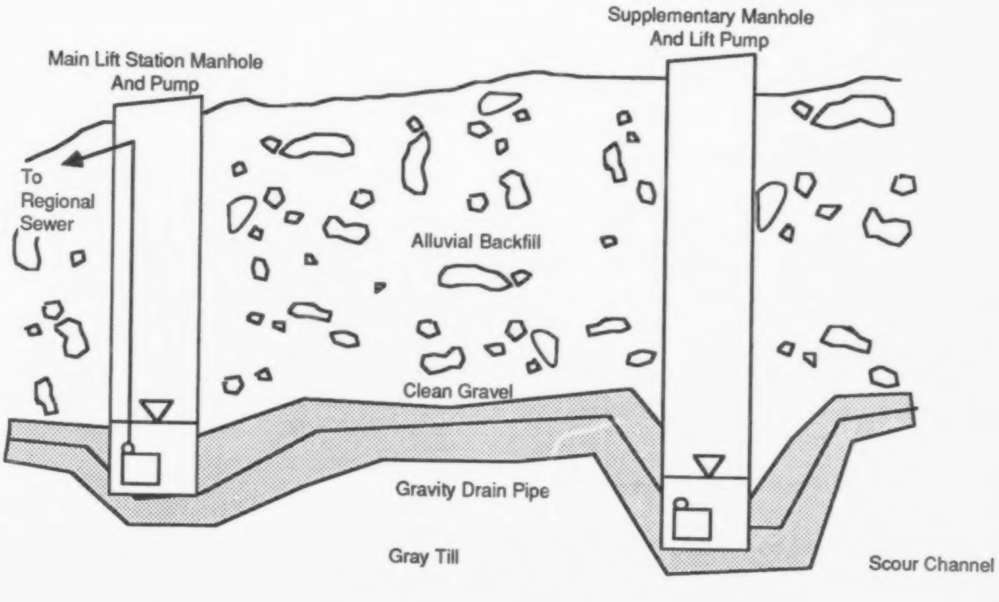
Filters and envelopes are often used in the construction of drain systems. The primary function of a filter is to prevent soil particles from entering and clogging the drain. Filters should always be used where soils have a high percentage of fines. Filter fabrics may be clogged by highly viscous fluids.

Figure 5-22. **The effect of relief and interceptor drains in altering the configuration of the water table (U.S. EPA 1985d).**


Relief Drains
Ground-Water Flow
Water Table
Water Table
I
d_e
H
L
L_e
D
Barrier
Barrier

I = Hydraulic gradient
d_e = Effective depth of the drain
L_e = Downslope influence of the drain
L = Drain spacing
H = Hydraulic head
D = Depth below drains to the impermeable barrier

Figure 5-23. **Subsurface drain with a lift station (Giddings 1982).**


Supplementary Manhole And Lift Pump
Main Lift Station Manhole And Pump
To Regional Sewer
Alluvial Backfill
Clean Gravel
Gravity Drain Pipe
Gray Till
Scour Channel

(View Looking Toward Site)

The function of an envelope is to improve water flow and to reduce flow velocity into the drains by providing a material that is more permeable than the surrounding soil. Envelopes also may be used to provide suitable bedding for a drain and to stabilize the soil material on which the drain is being placed. Envelopes are required for most applications.

Although filters and envelopes have distinctly different functions, well-graded sands and gravels can be used to meet the requirements of both a filter and an envelope. Geotextiles are also widely used as filters. These are generally made of polypropylene, polyethylene, polyester, or polyvinyl chloride. Selection of filter fabric should be based on its compatibility with the contaminants.

Manholes are used in subsurface drainage systems to serve as junction boxes between drains, silt and sand traps, observation wells, and access points for pipe location, inspection, and maintenance. Manholes should be located at junction points, changes in alignment or grade, and other designated points. No criteria have been established for manhole spacing.

Contaminated ground water or free product is collected by gravity flow in a drainage sump, from which it is pumped to treatment or recovery systems (Figure 5-24). The major steps in designing the sump and pumping system include (Bureau of Reclamation 1978):

- Determining the maximum inflow to the sump.
- Determining the amount of storage required.
- Determining the pumping rate.

$$Q_m = (S_v + Q_p t_p)/t_p$$

where

Q_m = pumping rate, ft³/min
S_v = storage volume, ft³
Q_p = maximum inflow, ft³/min
t_p = running time of the pump, min

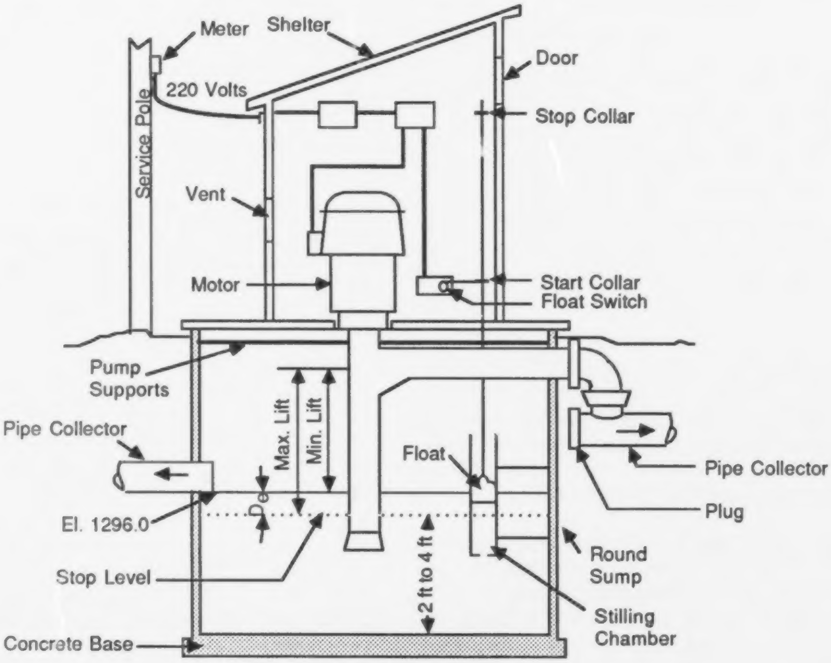
- Determining the start, stop, and discharge levels.
- Determining the size of the sump.
- Selecting the pump.

Construction Considerations

The major activities associated with construction of subsurface drains are trench excavation, trench stabilization, and installation of the drains, the filter, and the envelope materials.

Trench excavation is critical in the determination of the cost-effectiveness of drains. The need for extensive rock fragmentation and relocation of subsurface utilities may preclude the use of drains as a cost-

Figure 5-24. Typical design of an automatic drainage pumping plant (Bureau of Reclamation 1978).



effective correction action. Trenches are usually excavated by trenching machines or backhoes. Cranes, clamshells, and draglines are also used for deep excavation. The factors that influence the rate of trenching include 1) soil moisture; 2) soil characteristics such as hardness, stickiness, and stones; and 3) the depth and width of the trench.

Trenchers used for continuous trenching can be equipped with back-end modifications to provide shoring, to install a geotextile envelope, to lay tile or flexible piping, to blind the piping, and to backfill with gravel or excavated soil. Backhoes can excavate earth and fragmented rock for a trench the width of up to one-half of the bucket diameter and to depths of up to 70 to 90 feet.

The crane and clamshell can be used for deeper excavations or when access excludes the use of a backhoe. The use of draglines is generally limited to removal of loose rock and earth.

Excavation of a trench through material containing numerous large boulders or hard rock layers results in considerable construction delays and substantially increases the cost of construction. Typically, these materials must be fractured to facilitate their removal.

Proper grade control in a subsurface drain ensures against ponding of water and provides for a nonsilting velocity in the drainage pipe. Proper grade control can be accomplished either by automatic laser or by visual grade-control systems. Laser systems are adaptable to a wide range of earth-moving equipment, including trenchers and backhoes.

Proper installation of drains (maintenance of grades, placement and alignment of pipes) generally requires dewatering to produce a dry environment. Three basic options are available for dewatering: open pumping, predrainage with wellpoints or well systems, and ground-water cutoff. These techniques may be used separately or in combination.

Once trench excavation is completed, the components of the subsurface drain can be installed. This process includes laying the pipes, filter, and envelope material; backfilling; and installing auxiliary components.

All subsurface drains must be laid on a stable bed with the desired grade. Trenches that have inadvertently been overexcavated should be refilled with dry soil and brought to grade with envelope material. Well-graded gravel is then laid in an even layer several inches thick to provide bedding for the pipes.

Gravel envelopes are installed around the pipe drain to increase flow into the drain and to reduce the buildup of sediments in the drain line. They may be placed by hand, backhoe, or hopper cart or truck. In continuous trencher drain installation machines, gravel filling may be ongoing along with other operations. Filter fabrics are sometimes installed around the gravel envelope to prevent fines from clogging the envelope and drain pipe.

After the gravel envelope has been installed, the trench must be backfilled to the original grade. Prior to backfilling, the drain should be inspected for proper elevation below ground surface, proper grade and alignment, broken pipe, and thickness of the gravel envelope. The inspector should ensure that pipe drains and manholes are free of deposits of mud, sand, and gravel, or other foreign matter, and that they are in good working condition. Unstable soils may preclude all but spot checks before backfilling.

When installation of the subsurface drain is complete, the drain should be tested for obstructions. For a small drainage system, this can be done visually by shining a high-powered flashlight through a drain from one manhole and observing the beam in another. Television camera inspections can be used for large-diameter drains. Mechanical methods can be used to remove obstructions and to test for obstructions. Flexible polyurethane foam plugs are available that expand to wipe or scrape the pipe when water or air pressure is applied. They are also available with a rope through the center so they can be pulled through the drain (Knapp, Inc. 1982).

Manholes and silt traps should be checked frequently for the first year or two of operation for sediment buildup. Less frequent inspection is required as the system ages.

Piezometers may be installed in the various parts of the drainage system to identify operational problems with the filter, envelope, pipe, or other components of the system. Piezometers can measure the loss of head through a medium and thereby identify obstructions to flow, such as a clogged envelope or filter.

Malfunction of subsurface drains can be attributed to chemical clogging, clogging due to biological slimes, or a variety of physical mechanisms. Problems caused by these conditions are usually apparent at the surface above the drain. Inspection of the area will reveal soft or ponded surface conditions, areas of subsidence, and areas of accelerated vegetative growth. Chemical clogging of pipes and envelope materials can occur by a number of mechanisms. Calcium carbonate precipitates and iron and manganese deposits can build up around collector pipes or can cause cementation of the envelope material.

5.4.2.4 Costs

Costs for installation and operation of subsurface drains can be divided into four categories: installation costs, materials costs, engineering supervision, and operation and maintenance.

Installation costs depend primarily on the depth of excavation, stability of soils, extent of rock fragmentation required, and ground-water flow rates. The principal materials costs are for pipes, gravel, manholes, pumps, and other accessories for the drainage sump. Combined materials and installation unit costs are summarized in Tables 5-14 through 5-16.

Engineering and supervision involve such activities as staking the drain line, checking for grade control and alignment, and checking pipe specification and pipe quality. For the installation of subsurface drains in conventional agricultural and water conservation applications, engineering and supervision costs usually run about 5 to 10 percent of the total cost. These costs can be expected to be substantially higher for UST site applications, however, and will vary considerably depending on the geologic and hydrogeologic conditions.

Capital costs associated with the installation of subsurface drains are typically much higher than those associated with pumping systems. This is particularly true where substantial rock excavation is required and where deep drains requiring extensive shoring are needed. These factors may preclude consideration of drains as a cost-effective remedial action; however, operation and maintenance costs associated with drains are generally lower than those associated with pumping if the system is properly designed and maintained. Lower operation and maintenance costs become significant, particularly when plume removal or containment is needed over a long period of time.

As with other remedial technologies, total capital costs for drainage systems can vary widely with site conditions. Two scenarios are briefly described here to illustrate how widely capital costs may range.

At one particular hazardous waste site (Site A), a 261-foot-long interceptor drain was installed to a depth of 12 to 17 feet. The leachate discharged into a 4-foot-wide, 20-foot-deep sump that pumped the leachate at a rate of 18 to 20 gal/min to a treatment system (EPA 1984; JRB Associates 1985). Construction of the drainage system involved excavation of a 4- to 6-foot-wide trench, which was supported with steel sheet piling during construction. The trench was lined with filter fabric, 6 inches of gravel, and a 12-inch, perforated, concrete asbestos drain pipe. Additional filter fabric supported by screening was then wrapped around the pipe prior to backfilling. The total cost of the drainage system was $269,721 or $67 to $88/ft^2 (adjusted to 1986 dollars) (EPA 1984; JRB Associates 1985). Table 5-17 shows how the total capital costs were distributed.

A second case history involved installation of a shallow (3-foot-deep) interceptor trench at the A. W. Mauthe site in Appleton, Wisconsin (EPA 1984). The drainage system was approximately 750 feet long and consisted of 4-inch PVC drainage pipe laid in a gravel-filled trench. Four-foot-diameter concrete sumps were installed at two collection points and connected by about 25 feet of PVC pipe so that the water collected in one sump could be pumped to the other sump. The total capital cost of the drainage system was about $15,800 (updated to 1986 costs using ENR Construction Cost Indices). This cost estimate, however, also includes the cost of a 300-foot-long surface-water-diversion drainpipe. Therefore, the unit cost of the subsurface drain was less than $7.05/ft^2 (EPA 1984).

These two case histories show an order of magnitude difference in the unit cost for subsurface drainage systems. Probably the most significant factor contributing to these cost differences is the depth of the drain. In the case of Site A, the trench was excavated to a depth of 12 to 17 feet and shoring was required to support the trench wall. In the case of the Mauthe site, the subsurface drainage system was only 3 feet deep and trench excavation was greatly simplified.

5.5 Subsurface Barriers

The term "subsurface barriers" refers to low-permeability cutoff walls or diversions installed belowground to contain, capture, or redirect ground-water flow in the vicinity of a site. The most commonly used subsurface barriers are slurry walls, particularly soil-bentonite slurry walls. Less common are cement-bentonite or concrete (diaphragm) slurry walls, grouted barriers, and sheet piling cutoffs. For shorter periods of time (6 months or less), barriers can also be created by artificial freezing techniques. Another containment system involves the use of injection wells to form hydraulic barriers that both contain a plume and facilitate product recovery. These types of subsurface barriers are discussed in the following subsections.

5.5.1 Slurry Walls (EPA 1985a)

5.5.1.1 General Description

Slurry walls are the most common subsurface barriers because they provide a relatively inexpensive means of greatly reducing ground-water flow in unconsolidated earth materials. All slurry walls have one thing in common: they are all constructed in a vertical trench excavated under a slurry (Figure 5-25). The slurry, usually a mixture of bentonite and water, acts essentially as a drilling fluid. It hydraulically shores the trench to prevent collapse and simultaneously forms a filter cake on the trench walls to prevent heavy fluid losses into the surrounding ground. The different types of slurry walls are differentiated by the materials used to backfill the trench. Usually, an engineered soil mixture is blended with the bentonite

Table 5-14. 1986 Unit Costs for Trench Excavation and Associated Activities

Item	Assumptions	Unit Cost ($)	Source*
Trench excavation			
Trencher, ladder type	Gas, 5 ft deep, 8 in. wide	500/day	(1)
	Diesel, 8 ft deep, 16 in. wide	670/day	(1)
Backhoe, hydraulic	4-ft-wide trench, damp sandy loam		
	1 yd^3 capacity, 12 ft deep, 90 LF†/day	2.26/yd^3	(2)
	1.25 yd^3 capacity, 14 ft deep, 90 LF/day	2.17/yd^3	(2)
	2.5 yd^3 capacity, 18 ft deep, 115 LF/day	1.74/yd^3	(2)
	3.5 yd^3 capacity, 20 ft deep,136 LF/day	1.44/yd^3	(2)
Dragline	1.75 yd^3 capacity, 35 yd^3 /h	3.08/yd^3	(1)
	1.5 yd^3 capacity, 65 yd^3 /h	1.98/yd^3	(1)
Clamshell	0.5 yd^3 capacity, 20 yd^3 /h	4.96/yd^3	(1)
	1.0 yd^3 capacity, 35 yd^3 /h	3.32/yd^3	(1)
Rock fragmentation			
Jackhammer	---	40/h	(2)
Track-mounted air drill	---	76/h	(2)
Wall stabilization			
Sheet piling	Includes pull and salvage:		
	15 ft excavation, 22 lb/ft^2	7.34/ft^2	(1)
	25 ft excavation, 38 lb/ft^2	8.52/ft^2	(1)
	40 ft excavation, 38 lb/ft^2	7.91/ft^2	(1)
Wooden shoring	Includes wales, braces, and spacers; pull and salvage:		
	14 ft excavation	5.96/ft^2	(1)
	20 ft excavation	6.94/ft^2	(1)
H-piles	H-piles with 3-in. wood sheeting, horizontal between piles; includes removal of wales and braces:		
	15 to 22 feet	20 to 23/ft^3	(1)
	23 to 35 feet	22 to 25/ft^3	(1)
	36 to 45 feet	25 to 28/ft^3	(1)
	46 to 57 feet	30 to 32/ft^3	(3)
Dewatering			
Sump hole	Includes excavation and gravel:		
	with 12-in. corrugated pipe	20.23/ft^3	(1)
	with 15-in. corrugated pipe	26/ft^3	(1)
	with 18-in. corrugated pipe	29/ft^3	(1)
	with 24-in. corrugated pipe	39/ft^3	(1)
Opening pumping	Pumping 8 h, attended 8 h; includes 20 feet of suction hose and 100 feet of discharge hose:		
	2-in. diaphragm pump	365/day	(1)
	4-in. diaphragm pump	401/day	(1)
	3-in. centrifugal pump	366/day	(1)
	6-in. centrifugal pump	442/day	(1)

Table 5-14. (Continued)

Item	Assumptions	Unit Cost ($)	Source*
Submersible centrifugal sump pump	Bronze, without installation:		
	1/4 hp, 22 gpm, 10 ft head	205/each	(1)
	1/2 hp, 68 gpm, 10 ft head	334/each	(1)
	1/2 hp, 94 gpm, 10 ft head	442/each	(1)
	Cast iron, without installation:		
	1/4 hp, 23 gpm, 10 ft head	97/each	(1)
	1/3 hp, 35 gpm, 10 ft head	108/each	(1)
	1/2 hp, 68 gpm, 10 ft head	226/each	(1)
Diaphragm pump	Cast iron starter and level control, witout installation; 2-in. discharge:		
	10 gpm, 20 ft head	313/each	(1)
	60 gpm, 20 ft head	411/each	(1)
	120 gpm, 20 ft head	770/each	(1)
	160 gpm, 20 ft head	1207/each	(1)
Wellpoint dewatering	See Section 5.1 for costs	—	
Ground-water cutoffs	See Sheet Piling, above, for costs	—	
Grade control			
Automatic laser control		144/day	(1)

* Data from (1) Godfrey 1984a; (2) Godfrey 1984b; (3) McMahon 1984, adjusted to mid-1986 dollars.
† LF = linear feet.

Table 5-15. **1986 Unit Costs for Pipe Installation**

Item	Assumptions	Unit Cost ($)	Source*
Drain pipe			
PVC perforated underdrain	10-foot length, S.D.R. 35:		
	4-in.	2.22/ft	(2)
	6-in.	3.74/ft	(2)
	8-in.	4.68/ft	(2)
	10-in.	6.98/ft	(2)
	12-in.	8.63/ft	(2)
Corrugated steel or aluminum, perforated, asphalt-coated	6-in., 18-ga	4.76/ft	(1)
	8-in., 16-ga	6.37/ft	(1)
	10-in., 16-ga	8.22/ft	(1)
Porous wall concrete underdrain, extra strength	6-in.	4.25/ft	(1)
	8-in.	5.96/ft	(1)
	10-in.	8.99/ft	(1)
Vitrified clay, extra-heavy-duty strength, premium joints	4-in.	4.58/ft	(2)
	5-in.	5.49/ft	(2)
	6-in.	6.52/ft	(2)
	8-in.	8.73/ft	(2)
Filter and envelope			
Filter fabric	Polypropylene laid in trench	1.17 to 1.53/yd^2	(2)
Gravel envelope	Crushed bank run, screened 0.75- to 0.50-in., in trench	9.45 to 10.83/yd^3	(1)
Backfill			
Dozer backfill, no compaction	Up to 300-foot haul, 900 yd^3/day	1.14/yd^3	(1)
Dozer backfill, air-tamped	Up to 300-foot haul, 235 yd^3/day	5.60/yd^3	(1)
Compacted backfill, vibrating roller	6- to 12-in. lifts, 700 yd^3/day	1.58/yd^3	(1)
Compacted backfill, sheepsfoot roller	6- to 12-in. lifts, 650 yd^3/day	1.72/yd^3	(1)

* Data from (1) Godfrey 1984a; (2) Godfrey 1984b.

Table 5-16. **1986 Installed Costs for Manholes***

Item	Assumptions	Cost ($)
Concrete slab, cast in place, 8 in. thick	6 ft deep	915
	8 ft deep	1310
	12 ft deep	1965
	16 ft deep	2625
	20 ft deep	3280
Precast concrete riser pipe, 4-ft inside diameter	6 ft deep	585
	8 ft deep	795
	12 ft deep	1205
	16 ft deep	1620
	20 ft deep	2030
6-ft inside diameter	6 ft deep	1285
	8 ft deep	1720
	12 ft deep	2600
	16 ft deep	3485
	20 ft deep	4370
Slab tops, precast, 8 in. thick	4-ft diameter	80
	5-ft diameter	200
	6-ft diameter	275
Frames and covers, watertight	24-in. diameter	355
	32-in. diameter	440

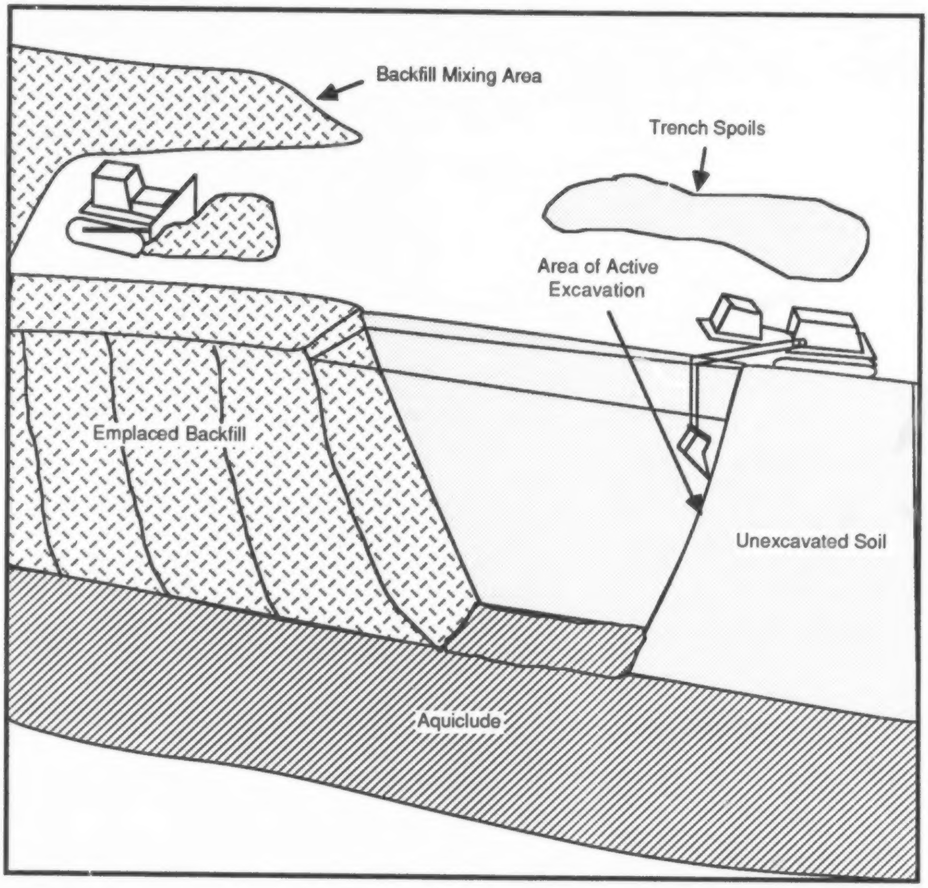
[*] Data from Godfrey 1984a.

Table 5-17. **Capital Costs for Interceptor Drain Installation***

Item	Cost† ($)
Materials	
550 feet of 12-in. perforated asbestos cement drainage pipe (only about 261 feet were actually used)	3,909
147 feet of 2-in. carbon steel pipe for carrying leachate to treatment system	1,591
2 submersible pumps and accessories	1,069
2,700 ft^2 vinyl-coated wire screen	721
338 yd^2 filter fabric	284
Other materials costs not given	459
Subtotal	12,033
Labor /Equipment	
Labor, equipment rental including excavation equipment and sheet piling and gravel fill	64,290
Company in-house labor	669
Total	76,992

[*] Data from EPA 1984.
[†] 1986 dollars.

Figure 5-25. **Slurry trench construction (Spooner et al. 1984).**



slurry and placed in the trench to form a soil-bentonite (SB) slurry wall. In some cases, the trench is excavated under a slurry of portland cement, bentonite, and water, and this mixture is left in the trench to harden into a cement-bentonite (CB) slurry wall. In those rare cases when great strength is required of a subsurface barrier, precast or case-in-place concrete panels are constructed in the trench to form a diaphragm wall.

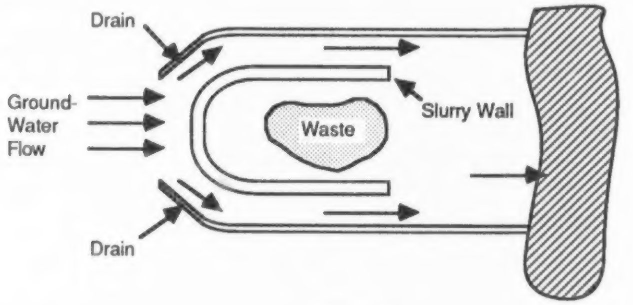
5.5.1.2 Application/Availability

As shown in Figure 5-26, slurry walls can be placed (relative to the direction of ground-water flow) upgradient, downgradient, or completely surrounding the site of contamination. Circumferential installations, by far the most common, offer several advantages. This placement vastly reduces the amount of uncontaminated ground water entering the site on the upgradient side. Also, if no compatibility problems exist between the contamination and the wall materials, it will reduce the amount of contamination leaving the downgradient side of the site. Moreover, the use of this configuration in conjunction with an infiltration barrier and a collection system (or other means of reducing the hydraulic head on the interior of the wall) can maintain the hydraulic gradient in an inward direction, which prevents escape of the contamination.

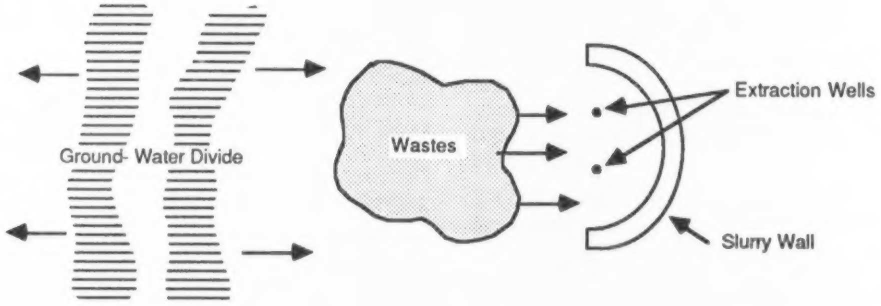
5.5.1.3 Design and Construction Considerations

Many factors must be considered in the design of a slurry wall. First, a detailed, design-phase investigation must be made to characterize subsurface conditions and materials as well as to address the disposition and nature of the contamination. The issue of wall compatibility also should be addressed early in the design stage by permeability testing of the proposed backfill mixture with actual site materials. The design-phase investigation results can be used to decide on the optimum configuration and to select any ancillary measures needed to enhance the

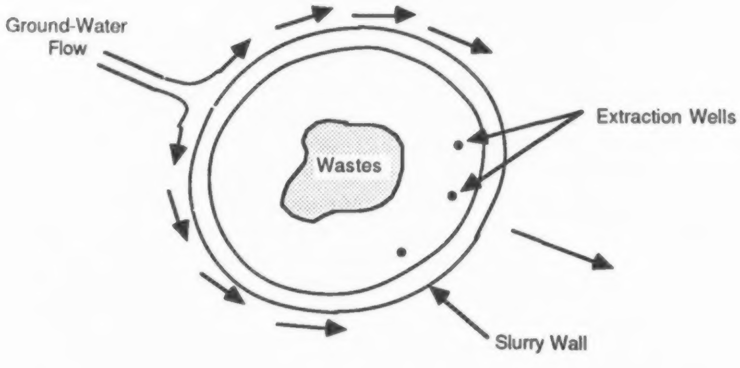
Figure 5-26. **Slurry wall placement (Spooner et al. 1984a).**


Drain
Ground-
Water
Flow
Slurry Wall
Waste
Drain

Upgradient


Extraction Wells
Wastes
Ground- Water Divide
Slurry Wall

Downgradient


Ground-Water
Flow
Extraction Wells
Wastes
Slurry Wall

Circumferential

performance of the wall. These and other design considerations are covered in great detail in a report by the EPA entitled Slurry Trench Construction for Pollution Migration Control (Spooner et al. 1984).

Construction of a slurry wall is relatively straightforward. The required equipment depends on the depth and length of the wall. For walls up to 80 feet deep, a backhoe or modified backhoe is used for excavation. Deeper installations require the use of a mechanical or hydraulic clamshell or, in rare cases, a dragline. In small-volume wall installations batch slurry and backfill-mixing systems may be used, whereas large jobs require flash slurry mixers and a large backfill mixing area.

Regardless of the equipment used, the slurry is introduced just after the trench is opened and before the water table is reached. The primary function of the slurry is to act as hydraulic shoring to prevent trench collapse. There is also evidence to indicate that the filter cake formed on the trench walls by the slurry contributes to the low permeability of the completed wall.

Proper quality control during wall installation is essential. It is most important that checks be made of trench continuity and backfill mixing and placement. For backhoe-excavated trenches, the continuity of the trench is relatively easy to verify. Inspection of the excavated material indicates when and where the confining layer is encountered, and observing the motion of the backhoe arm will confirm lateral continuity. With clamshell excavators, confirmation of lateral continuity may be more complicated.

5.5.1.4 Costs

Costs of slurry walls are highly site-specific. A typical installation based on a trench 4 ft wide x 40 ft deep x 100 ft long filled with bentonite/water slurry would cost approximately $310 per linear foot of trench (updated to 1986 dollars).

5.5.2 Grouting (EPA 1985a)

5.5.2.1 General Description

Grouting refers to a process whereby one of a variety of fluids is injected into a rock or soil mass, where it is set in place to reduce water flow and strengthen the formation. Because they are costly, grouted barriers are seldom used to contain ground-water flow in unconsolidated materials around hazardous waste sites. Slurry walls are less costly and have lower permeability than grouted barriers. Consequently, in remediation efforts at contaminated sites, grouting is best suited for sealing voids in rock. Even when rock voids are transmitting large water volumes, a grout can be formulated to set before it is washed out of the formation.

5.5.2.2 Application/Availability

Cement has probably been used longer than any other type of material for grouting applications. For cement grouting, hydraulic cement that sets, hardens, and does not disintegrate in water is used. Because of the large particles they contain, cement grouts are more suitable for rock than for soil applications. The addition of clay or chemical polymers to the grout, however, can improve its range of usage. Cement grouts have been used in both soil consolidation and water cutoff applications, but their use is normally restricted to more open soils.

Clays have been widely used as grouts, either alone or in formulations, because they are inexpensive. Only certain types of clay minerals will swell in the presence of water and form a gel structure at low-solution concentrations.

Bentonite grouts can be used alone as void sealers in coarse sands. Bentonite-chemical grouts can be used on medium to fine sands. Both of these grout types can also be used to seal small rock fissures; because of their low gel strengths, however, they cannot support structures.

Alkali silicates receive the largest and widest use of the chemical grouts. Sodium, potassium, and lithium silicates are available, but sodium silicates are used most often. Silicate grouts are used for both soil consolidation and void sealing. Unless preceded by cement grouting, however, they are not suitable for open fissures or highly permeable materials because of syneresis (water expulsion).

Organic polymer grouts represent only a small fraction of the grouts in use. These grouts consist of organic materials (monomers) that polymerize and cross-link to form an insoluble gel. The organic polymer grouts include acrylamide, phenolic, urethane, urea-formaldehyde, epoxy, and polyester grouts.

The compatibility of these grouts with petroleum and other chemical substances has not been studied in great detail; only general incompatibilities are known. Whenever grouting is considered as a remedial option, thorough compatibility testing must be performed.

5.5.2.3 Design and Construction Considerations

The design of a grout system must be based on a thorough site characterization. Analysis of site characterization data, including boring logs, pump or injection test results, and other data, is used to determine if a site lends itself to the application of a grout barrier and which grout is most suitable based on viscosity, compatibility, and ultimate permeability. This is a very involved process and should be conducted by an experienced engineer.

Construction of a grout barrier is accomplished by pressure-injecting the grouting material through a pipe into the strata to be waterproofed. The injection points are usually arranged in a triple line of primary and secondary grout holes (Figure 5-27). A predetermined quantity of grout is pumped into the primary holes and after it has had time to gel, grout is injected into the secondary holes. The secondary grout holes are intended to fill in any gaps left by the primary grout injection.

5.5.2.4 Costs

Table 5-18 presents approximate costs of some common grouts.

Table 5-18. Costs of Common Grouts*

Grout Type	Approximate Cost of Solution ($/gal†)
Portland cement	1.37
Bentonite	1.81
Silicate	
20 percent	1.81
30 percent	3.03
40 percent	3.96
Epoxy	43.29
Acrylamide	9.59
Urea-formaldehyde	8.22

*Data from Spooner et al. 1984b.
†1986 dollars.

5.5.3 Sheet Piles (EPA 1985a)

5.5.3.1 General Description

Sheet piling can be used to form a ground-water barrier. Sheet piles can be made of wood, precast concrete, or steel. Wood is an ineffective water barrier, however, and concrete is used primarily where great strength is required. Steel is the most effective in terms of ground-water cutoff and cost.

5.5.3.2 Application/Availability

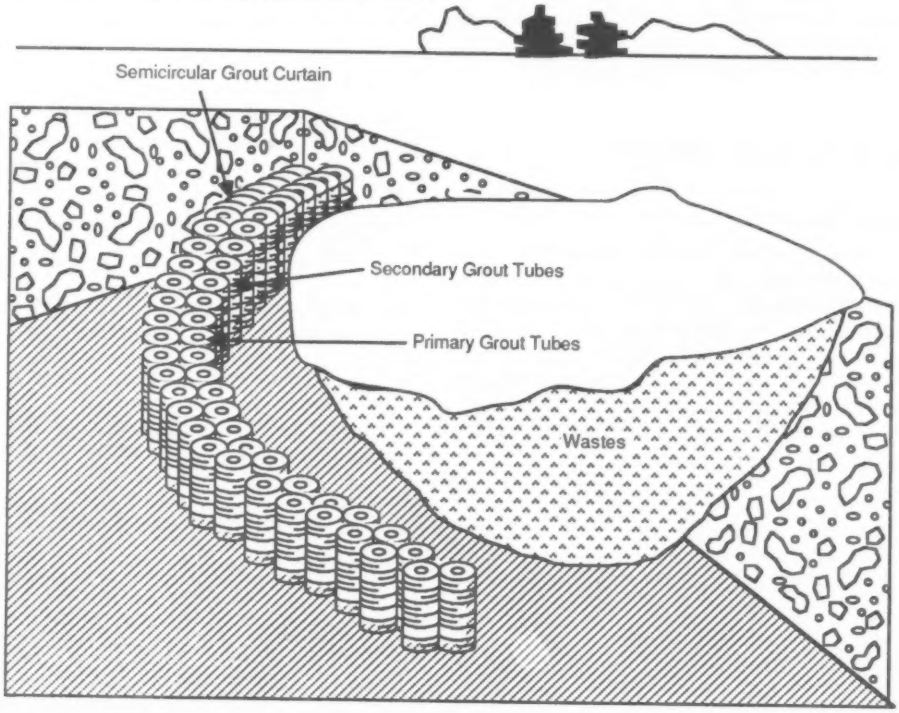
Steel sheet piling is seldom used as a ground-water barrier because costs are high and wall integrity is unpredictable. It is used more frequently for temporary dewatering in other construction or as erosion protection where some other barrier, such as a slurry wall, intersects flowing surface water.

One of the largest drawbacks of sheet piling, or any other barrier technology requiring pile driving, is that rocky soils tend to damage or deflect the piles and may render this approach ineffective as a ground-water barrier.

5.5.3.3 Design and Construction Considerations

The primary design parameters for any barrier are its dimensions and permeability. Dimensional requirements, which are based on site characteristics, are

Figure 5-27. Semicircular grout curtain (Spooner et al. 1984b).



straightforward. Depth limitations are governed by the soil material at the site. On the other hand, design factors for ultimate permeability of the cutoff are more complicated and must assume some factor to account for leakage through the interlocking joints.

Typical steel piling shapes and interlocks are illustrated in Figure 5-28. For construction of a sheet piling cutoff, the pilings are assembled at their edge interlocks before they are driven into the ground to ensure that earth materials and added pressures will not prevent a good lock between piles. The piles are then driven a few feet at a time over the entire length of the wall. This process is repeated until the piles are all driven to the desired depth.

When first placed in the ground, sheet piling cutoffs are quite permeable. The edge interlocks, which are necessarily loose to facilitate placement, allow the easy passage of water. With time, however, fine soil particles are washed into the seams and water cutoff is effected. The time required for this sealing to take place depends on the rate of ground-water flow and the texture of the soil involved. In very coarse, sandy soils, the wall may never seal. In such cases, it is possible to grout the piling seams, but this is a costly procedure.

5.5.3.4 Costs

Costs of installed steel sheet piling will vary with depth, total length, type of pile (coated or uncoated), and relative ease of installation. Average costs range from approximately $6.68 per square foot up to approximately $16.43 per square foot.

5.5.4 Hydraulic Barriers (CONCAWE 1979)

5.5.4.1 General Description

A plume of contaminated ground water can be contained or manipulated by pumping and injection wells. Similar to water-table adjustment, cones of depression or recharge in the water table are developed to modify prevailing hydraulic gradients. The movement and size of a plume can be manipulated by various pumping recharge strategies. Recovered water may be treated at the surface and reinjected as part of the plume-containment program.

5.5.4.2 Application/Availability

Hydraulic barrier technology can be applied to most contaminated sites, particularly those directly underlain by moderate to highly productive aquifers. The use of low-flow interdiction wells to control hydrocarbon plumes in ground water has been demonstrated successfully (Sammons and Armstrong 1986). The principle of plume control by hydraulic methods is to effect a change in the ground-water flow pattern such that the contaminant can be drawn to a specific control point or points. This can be achieved by discharging or recharging the aquifer or a combination of both. The success of the method depends on maintaining an artificial gradient in the ground-water surface.

5.5.4.3 Design and Construction Considerations

Establishing a hydraulic barrier requires strategic placement of a series of injection wells. The location and depth of these wells should be determined by detailed examination of the site. Low-permeability soil (clay, shale) and fractured or consolidated rock aquifers limit the effectiveness of pumping/recharge systems.

Required equipment includes a drilling rig (usually truck-mounted) for well construction, a backhoe or bulldozer for digging a recharge trench (if appropriate), pumps for water withdrawal, and electricity to operate the pump motor. Drilling in contaminated soil or water will require special protection of workers.

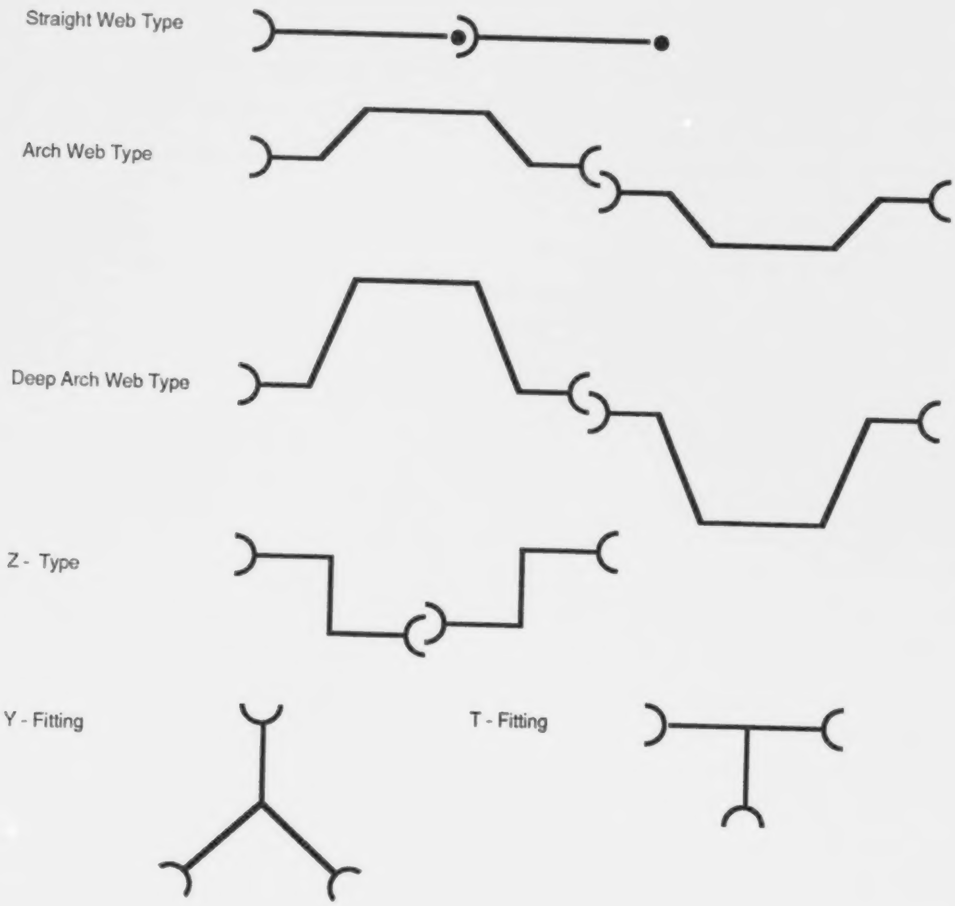
5.5.4.4 Costs

Estimated costs were computed for a series of 6-inch-diameter pumping and recharge wells connected by 8-inch transfer piping, 200 feet per pair of wells, with submersible pumps in the pumping wells and gravity discharge in the injection wells, an average well depth of 50 feet, and a pumping rate of 50 gal/min per well (500 gal/min for the site). These costs are as follows:

Pumping/recharge wells	$27.73 per linear foot
Transfer piping (PVC material)	10.78 per linear foot
Total	$38.51 per linear foot

Operation and maintenance is estimated to be $72.79 per thousand gallons pumped per day.

Figure 5-28. **Typical steel piling shapes and interlocks (U.S. EPA 1985a).**


Straight Web Type
Arch Web Type
Deep Arch Web Type
Z - Type
Y - Fitting
T - Fitting

5.6 In Situ Treatment

In situ treatment of contamination resulting from an UST leak offers an alternative to excavation and removal and conventional pumping and treating methods. In situ treatment processes are generally divided into three categories: biological, chemical, and physical. In situ biodegradation, or biostimulation, is based on the concept of stimulating microorganisms to decompose the contaminants of concern. In situ chemical treatment involves the injection of a specific chemical or chemicals into the subsurface to degrade, immobilize, or flush out the contaminants. Physical methods involve physical manipulation of the soil by the use of air, steam, heat, freezing, or other means. In many instances, a combination of in situ and aboveground treatment will achieve the most cost-effective treatment. Also involved are methods for delivering solutions to the subsurface and methods for controlling the spread of contaminants and treatment reagents beyond the treatment zone.

Although not as developed as other currently available technologies for restoring contaminated soils and aquifers, some in situ treatment technologies have been demonstrated successfully in actual UST site remediations. Applicability of in situ methods must generally be determined on a site-specific basis after laboratory- and pilot-scale testing.

5.6.1 Soil Flushing (EPA 1985a)

5.6.1.1 General Description

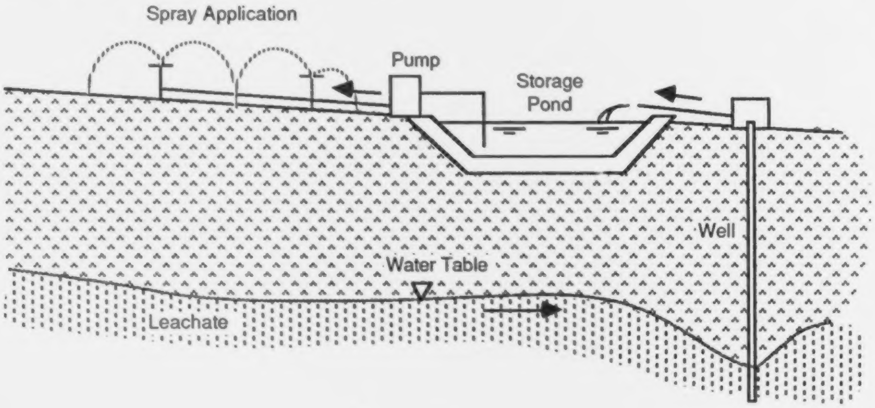
Organic and inorganic contaminants can be washed from contaminated soils by an extraction process called "soil flushing," "solvent flushing," "ground leaching," or "solution mining." Water or an aqueous solution is injected into or sprayed onto the area of contamination, and the contaminated elutriate is collected and pumped to the surface for removal, recirculation, or onsite treatment and reinjection (Figure 5-29). During elutriation, the flushing solution mobilizes the sorbed contaminants by dissolution or emulsification.

5.6.1.2 Application/Availability

Soil flushing technology is currently in the laboratory stage. Studies have been conducted to determine the appropriate solvents for mobilizing various classes and types of chemical constituents. The technology may be easy or difficult to apply, depending on the ability to flood the soil with the flushing solution and to install collection wells or subsurface drains to recover all the applied liquids. Provisions also must be made for ultimate disposal of the elutriate. The achievable level of treatment varies and depends on the contact of the flushing solution with the contaminants, the appropriateness of solutions for the contaminants, and the hydraulic conductivity of the soil. The technology is more applicable to highly permeable soils.

Water can be used to flush water-soluble or water-mobile organics and inorganics. Hydrophilic organics are readily solubilized in water. Organics amenable to water flushing can be identified according to their soil/water partition coefficients, or estimated based on their octanol/water partition coefficients. Organics considered soluble in the environmental sense are those with a partition coefficient (K) of less than about 1000. High-solubility organics, such as lower-molecular-weight alcohols, phenols, and carboxylic acids, and other organics with a coefficient less than 10 may already have been flushed from the site by natural flushing processes. Medium-solubility organics (K = 10 to 1000) that can be effectively removed from soils by water flushing include low- to medium-molecular-weight ketones, aldehydes, and aromatics, and lower-molecular-weight halogenated hydrocarbons, such as trichloroethylene (TCE) and tetrachloroethylene (PCE). Inorganics that can be flushed

Figure 5-29. Soil flushing system (Ehrenfeld and Bass 1983).



from soil with water are soluble salts such as the carbonates of nickel, zinc, and copper. Adjusting the pH with dilute solutions of acids or bases will enhance inorganic solubilization and removal. Soil flushing applicability is summarized in Table 5-19.

5.6.1.3 Design and Construction Considerations (Sims et al. 1985)

The following basic information is required for implementation of a soil-flushing process:

- Characterization and concentration of chemical constituents
- Depth, profile, and areal distribution of contamination
- Partitioning of chemical constituents between solvent(s) and soil
- Effects of flushing agent (solvent) on physical, chemical, and biological soil properties
- Suitability of site for flooding and installation of wells and/or subsurface drains
- Whether soil and site can tolerate traffic

Flushing solutions may include water, acidic aqueous solutions (sulfuric, hydrochloric, nitric, phosphoric, and carbonic acids), basic solutions (e.g., sodium hydroxide), and surfactants (e.g., alkylbenzene sulfonate). Water can be used to extract water-soluble or water-mobile constituents. Acidic solutions are used for metals recovery and for basic organic constituents, including amines, ethers, and anilines. Basic solutions are used for flushing metals, including zinc, tin, and lead, as well as for some phenols, complexing and chelating agents, and surfactants.

The addition of any flushing solution to a soil system requires careful management and knowledge of reactions that may adversely affect the system.

For example, a sodium addition (e.g., sodium hydroxide) to soil systems may adversely affect soil permeability by altering the soil/sodium adsorption ratio. The user must understand both the chemical reaction(s) between solvent and solute, and those between solvent and site/soil system.

At a site contaminated by organic constituents, recycling the elutriate back through the soil for treatment by biodegradation may be possible. Proper control of the application rate would provide an effective in-place treatment for soil concentrations that would allow controlled biodegradation of the waste constituents. This approach could eliminate the need for separate processes for treatment and disposal of the collected waste solution, or at least provide for a combination pretreatment/land application, which could be considerably more economical than unit operations for treatment of elutriate.

Table 5-19. Applicability of Soil Flushing Techniques[*]

Compounds Amenable to Treatment	Flushing Solution	Process	Limitations
Hydrophilic compounds (high solubility, low K_{OW})	Water	Contaminated soils are flooded with water or a water/chemical mixture and the elutriated solution is collected	Not suitable for compounds that are adsorbed to soils
Hydrophobic compounds (low solubility, high K_{OW})	Aqueous solutions of surfactants	Contaminants are mobilized into solution by solubility formation of emulsion or reaction. Mobilized contaminants are collected	Some surfactants are easily degraded within the soil environment Extensive laboratory testing may be required to determine optimum mix of surfactant
Heavy metals	Dilute solutions of acids, bases, or chelates	Involves solubilizing the metals followed by extraction of the metal ions	Some metals are strongly sorbed and require treatment with strong acids, which may be toxic Some chelating agents will be sorbed by soils

[*] Data from Wagner and Kosin 1985.

When soils are contaminated with inorganic and organic constituents, a combination pretreatment/land application, in which the metal constituent(s) are reduced or eliminated in the elutriate by precipitation and the elutriate is then applied to the land, may be a feasible, cost-effective method of treatment.

Soil flushing and elutriate recovery may also be appropriate in cases where the use of chemical oxidizing or reducing agents for chemical degradation of waste constituents results in the production of large amounts of oxygenated, mobile, degradation products. The most conservative and safest approach may be to flush the soil after treatment for recovery and possible controlled reapplication of the elutriate to the soil surface.

Equipment used for soil flushing includes drains and an elutriate collection and distribution system. Solvents may also be required. Reapplication of collected elutriate may require construction of a holding tank for the elutriate.

5.6.1.4 Costs

Because the soil flushing technology is not widely used at this time, and because this approach is particularly site- and contaminant-related, cost information is scarce.

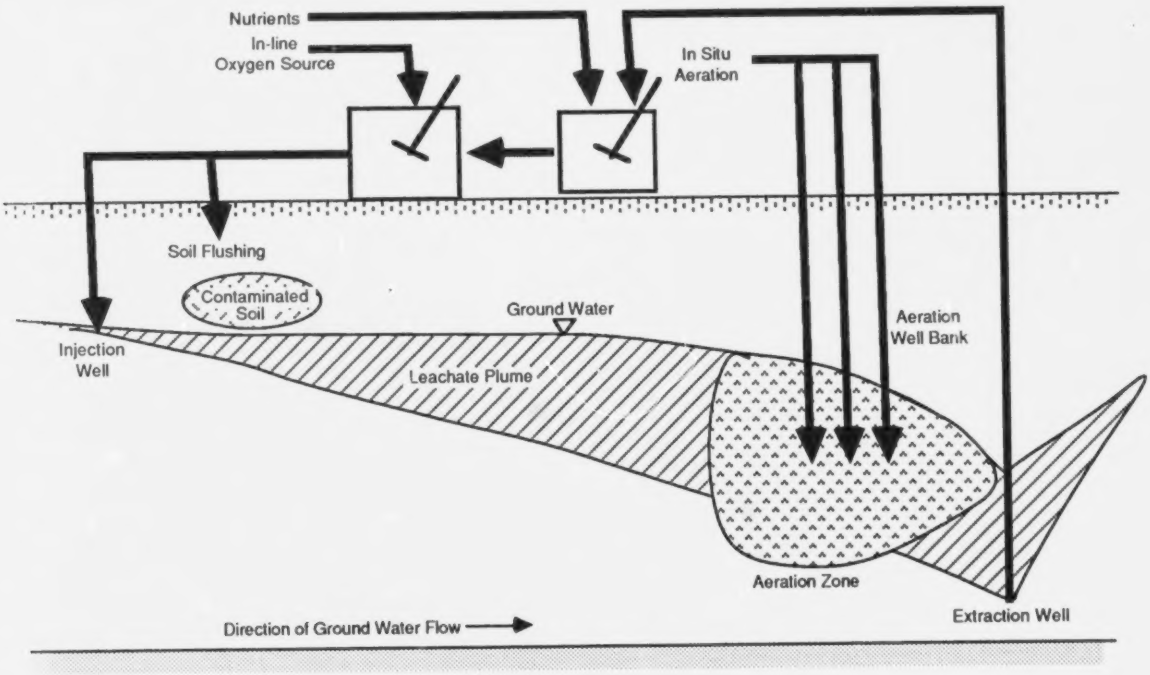
5.6.2 Biostimulation (EPA 1985a)

5.6.2.1 General Description

A site contaminated by a leaking UST might be restored through biostimulation, a technology whereby naturally occurring soil microorganisms are stimulated to biodegrade the waste. The basic concept involves altering environmental conditions to enhance microbial catabolism or cometabolism of organic contaminants, which results in the breakdown and detoxification of those contaminants. This technology has developed rapidly over recent years and appears to be one of the most promising of the in situ treatment techniques.

The biostimulation method that has been most developed and is most feasible for in situ treatment is one that relies on aerobic (oxygen-requiring) microbial processes. This method involves optimizing environmental conditions by providing an oxygen source and nutrients, which are delivered to the subsurface through an injection well or infiltration system for the enhancement of microbial activity (Figure 5-30). Indigenous microorganisms can generally be relied upon to degrade a wide range of compounds given proper nutrients and sufficient oxygen.

Figure 5-30. Biostimulation of soil and ground water (EPA 1985a).



In situ biodegradation technology also encompasses ground-water seeding, which refers to the addition of specially adapted or genetically manipulated microorganisms below the water table. (Some phases of ground-water seeding are covered by patents.)

5.6.2.2 Application/Availability

Considerable research conducted over the past several decades has confirmed that microorganisms can break down many of the organic compounds currently stored in underground tanks. Laboratory, pilot, and field studies have demonstrated that microorganisms can be used in situ to reclaim contaminated soils and ground water.

The feasibility of biostimulation as an in situ treatment technique is dictated by waste and site characteristics. The following factors determine the applicability of a biostimulation approach:

- Biodegradability of the organic contaminants
- Environmental factors that affect microbial activity
- Site hydrogeology

The most rapid and complete degradation of most compounds occurs aerobically. Some compounds, most notably the lower-molecular-weight halogenated hydrocarbons, will only degrade anaerobically. In general, aerobic techniques are most suitable for the degradation of petroleum hydrocarbons, aromatics, halogenated aromatics, polyaromatic hydrocarbons, phenols, halophenols, biphenyls, organophosphates, and most pesticides and herbicides. Anaerobic techniques under very reducing conditions appear to be most feasible for the degradation of lower-molecular-weight halogenated hydrocarbons such as unsaturated alkyl halides (e.g., PCE and TCE) and saturated alkyl halides (e.g., 1,1,1-trichloroethane and trihalomethane). Aerobic degradation in the presence of methane gas, however, appears to be promising for some low-molecular-weight halogenated hydrocarbons.

The availability of the compound to the organism also dictates its biodegradability. Compounds with greater aqueous solubilities are generally more available to degrading enzymes. For example, cis-1,2-dichloroethylene is preferentially degraded relative to trans-1,2-dichloroethylene. The most likely explanation for this is that "cis" is more polar than "trans" and is therefore more water-soluble. The use of surfactants can increase the solubility and therefore the degradability of compounds.

5.6.2.3 Design and Construction Considerations

The feasibility and effectiveness of biostimulation as an in situ treatment method is determined by the microbial population, the biodegradability of the organic contaminants, and a host of environmental factors that affect microbial activity (Wagner and Kosin 1985). High concentrations of leaked materials from an UST and deficient soil conditions (such as low moisture content) will adversely affect biodegradation, as will extremes of pH, temperature, and nutrient levels. In general, optimum environmental conditions are 1) pH of 7.0 to 8.5, 2) temperature of 15° to 35°C, 3) nutrient levels of nitrogen and phosphorus, and 4) 40 percent by weight moisture in soil. Adequate mixing (aeration or cultivation) is also needed.

Leaking substances from an UST can destroy the natural microbial population. For in situ biological treatment to remain a viable option, the factors that caused the sterilization must be corrected (e.g., neutralization with acid or base, or dispersing and diluting to a certain extent). Even though the native microbes have been destroyed, biological treatment is still possible by the deployment of specialized mutant strains of microbes; however, the value of mutant organisms (super bugs) is still being debated. These commercially produced strains are available in a fresh liquid state, a powdered state, or freshly reconstituted. The potentially harmful secondary effect of the addition of a foreign microorganism to the environment will generally be minor because once the hazardous material has been digested, the foreign-added microorganisms will probably die and become a source of nourishment for the naturally occurring microorganisms.

One problem associated with the addition of microorganisms to contaminated water is the significant increase in the consumption of dissolved oxygen. Low dissolved oxygen levels could prove to be detrimental to existing aquatic organisms. This problem can be minimized, however, by providing adequate aeration or adding only small amounts of bacteria so that excessive oxygen consumption does not occur.

Even if the active microbial population is substantial, the wastes are biodegradable. Parameters can be altered to optimize biodegradation in situ. Biostimulation is not feasible, however, if the hydrogeology of the site is not suitable. The hydraulic conductivity must be great enough and the residence time short enough so that added substances (oxygen and nutrients) are not "used up" before reaching the distal portions of the treatment zone. Sandy and other highly permeable sites are far easier to treat than sites containing clayey soils.

Added substances also can react with the soil components. Oxidizing the subsurface could result in the precipitation of iron and manganese oxides and hydroxides. If precipitation is extensive, the delivery system and possibly even the aquifer could become clogged. The addition of phosphates could result in the precipitation of calcium and iron phosphates. If calcium concentrations are high, the added phosphate can be tied up by the calcium and would therefore not be available to the microorganisms.

Oxygen can be provided to the subsurface through the use of air, pure oxygen, hydrogen peroxide, or possibly ozone. Air can be added to extracted ground water before reinjection, or it can be injected directly into the aquifer. The first method, known as in-line aeration, involves adding air into the pipeline and mixing it, with a static mixer for example. A pressurized line can increase oxygen concentrations, as can the use of pure oxygen.

The use of in situ aeration wells is a more suitable method for injecting air into contaminated plumes. A bank of aeration wells can be installed to provide a zone of continuous aeration through which the contaminated ground water would flow. Oxygen saturation conditions can be maintained for degrading organics during the residence time of ground-water flow through the aerated zone. The required time for aeration can be derived from bench-scale studies.

Microdispersions of air in water by the use of colloidal gas aprons (CGA) create bubbles 25 to 50 micrometers in diameter. This newly developed method holds promise as a means of introducing oxygen to the subsurface (Michelsen, Wallis, and Lavinder 1985). With selected surfactants, dispersions of CGA's can be generated that contain 65 percent air by volume.

A blower also can be used to provide the flow rate and pressure for aeration. At a ground-water bioreclamation project in Waldwick, New Jersey, 5 psi pressure was maintained in nine 10-foot aeration wells, each with an airflow of 5 ft^3/min (Groundwater Decontamination Systems, Inc. 1983).

Oxygenation systems, either in-line or in situ, can also be installed to supply oxygen to the biostimulation process. Their advantage over conventional aeration is that higher oxygen solubilities and hence more efficient oxygen transfer to the microorganisms can be attained. Solubilities of oxygen in various liquids are four to five times higher under pure oxygen systems than with conventional aeration. Therefore, in-line injection of pure oxygen will provide sufficient dissolved oxygen to degrade 20 to 30 mg/liter of organic material, assuming 50 percent cell conversion. The higher oxygen solubilities also may provide some flexibility in the design of cell banks, especially at greater pressures, because the oxygen may not be used up immediately as it is with aeration.

Hydrogen peroxide (H_2O_2) as an oxygen source has been used successfully at the cleanup of several spill sites. Hydrogen peroxide is cytotoxic at high concentrations, but research has demonstrated that it can be added to acclimated cultures at up to 1000 ppm without toxic effects. Hydrogen peroxide offers the following advantages:

- Greater oxygen concentrations can be delivered to the subsurface; 100 mg/liter H_2O_2 provides 50 mg/liter O_2.
- Less equipment is required to oxygenate the subsurface. Hydrogen peroxide can be added in-line along with the nutrient solution. Aeration wells are not necessary.
- Hydrogen peroxide keeps the well free of heavy biogrowth. Microbial growth and subsequent clogging is sometimes a problem in air injection systems.

Bioreclamation also requires the presence of nutrients in the soil to effect biodegradation. Nitrogen and phosphate are the nutrients most frequently present in limited concentrations in soils. Other nutrients required for microbial metabolism include potassium, magnesium, calcium, sulfur, sodium, manganese, iron, and trace metals. Many of these nutrients may already be present in the aquifer in sufficient quantities and need not be supplemented.

The optimum nutrient mix can be determined by laboratory growth studies and geochemical evaluations of the site. Caution must be exercised in evaluating microbial needs based on soil and ground-water chemical analyses. A chemical analysis does not necessarily indicate what is available to the microorganisms. In some cases, generalizations can be made; e.g., if calcium is present at 200 mg/liter (a very high concentration), calcium supplementation is likely to be unnecessary.

One of the major factors in determining the success of an in situ treatment system is to ensure that the injection and recovery systems are designed to accomplish the following:

- Provide adequate contact between treatment agents and contaminated soil or ground water.
- Provide hydrologic control of treatment agents and contaminants to prevent their migration beyond the treatment area.
- Provide for complete recovery of spent treatment solutions and/or contaminants where necessary.

The several design alternatives available for delivering nutrients and oxygen to the subsurface and for collecting and containing the ground water can generally be categorized as gravity-flow or forced methods. Most of the systems that have been used in biostimulation projects involve subsurface drains (gravity system), injection wells, and extraction wells.

The following criteria are important in the design of an injection/recovery system:

- The ground-water injection rate must be the same as the rate determined during the field testing program.
- All injected ground water and associated elements must be kept within the site boundary to prevent the transport of contaminants to adjacent areas. (This implies that some net ground-water pumpage will take place at the site.)
- The distance between the injection and pumping wells should be such that approximately six injection-pumping cycles can be completed within a 6-month period.

Implementation of a remedial action involving biostimulation will take longer than excavation and removal of contaminated soils. Depending on the specific site, it could also take longer than a conventional pumping and treating approach. The advantage of in situ biodegradation over the latter approach is that in situ biodegradation treats contaminated subsurface soils and thus removes the source of ground-water contamination.

5.6.2.4 Costs

Costs for biological in situ treatment are determined by the site's geology and geohydrology, the extent of contamination, the kinds and concentrations of contaminants, and the amount of ground water and soil requiring treatment. There is no easy formula for predicting costs. Costs provided for actual site cleanups indicate that biological treatment can be far more economical as an alternative to, or in conjunction with, excavation and removal or conventional pumping and treating methods.

Total capital and research and development costs for cleanup of the Biocraft site (Sims et al. 1985) were $950,137 including $458,330 for process development (R&D). Project costs also included a hydrogeological study as well as the design and operation of a ground-water injection and collection system and a biostimulation plant. Total operating costs, based on treating 13,680 gallons/day, were approximately $232/day or $0.0170/gal. The total cost, including amortization based on projected costs, was $0.0367/gal over a 3-year period. Prior to initiation of the biological treatment program, contaminated water had been removed at a rate of 10,000 gal/month, and the average disposal cost had been $0.36/gal. The cost of biological treatment of an equal number of gallons is an order of magnitude less than that for disposal. The Biocraft site used surface biological reactors and enhanced in situ treatment by reinfiltrating oxygen and nutrient-treated ground water. Costs of in situ treatment alone would have been less because they would not include the process plant design and equipment.

Table 5-20 presents the estimated site cleanup costs for hypothetical sites at which hydrogen peroxide is used as an oxygen source for the enhancement of in situ biodegradation. The cleanup of 300 gallons of gasoline from a sand/gravel aquifer (Site A) over a period of 6 to 9 months is estimated to cost $72,000 to $123,000. Cleanup of 2,000 gallons of diesel fuel from a fractured bedrock formation (Site B) is estimated to require 9 to 12 months and cost $164,000 to $257,000. The cost estimate for degrading 10,000 gallons of jet fuel from a fine gravel formation is estimated to cost $411,000 to $616,000 and take 14 to 18 months.

Table 5-20. Estimated Costs for Hypothetical Bioreclamations With Hydrogen Peroxide as an Oxygen Source[*]

	Site A	Site B	Site C
Contaminant	300 gallons gasoline	2,000 gallons diesel fuel	10,000 gallons jet fuel
Formation	Sand/gravel	Fractured bedrock	Fine gravel
Flow rate	50 gal/min	10 gal/min	100 gal/min
Project time	6 to 9 months	9 to 12 months	14 to 18 months
Estimated cost	$72,000 to $123,000	$164,000 to $257,000	$411,000 to $616,00

[*] Data from FMC, 1985.

5.6.3 *Chemical Treatment*

5.6.3.1 General Description

The term "in situ chemical treatment" covers a variety of technologies whereby organic and inorganic contaminants can be immobilized, mobilized for extraction, or detoxified. Technologies that fall into the "immobilization" category include precipitation, chelation, and polymerization. The technologies used to mobilize contaminants for extraction fall into the category of "soil flushing," which was covered in Subsection 5.6.1. "Detoxification" techniques include oxidation, reduction, neutralization, and hydrolysis.

These categories do not define the limits of each technology. For example, a treatment method that immobilizes a contaminant may also detoxify it; a flushing solution that mobilizes one contaminant may precipitate, detoxify, or increase the toxicity of another.

5.6.3.2 Application/Availability

The feasibility of an in situ treatment approach is dictated by site geology and hydrology, soil characteristics, and waste characteristics. The application of many chemical in situ treatment techniques to UST site reclamation is currently conceptual in nature or in the developmental stage; therefore, little hard data are available on the specific site characteristics that may limit the applicability of each method.

Table 5-21 summarizes the in situ chemical treatment methods for organics and inorganics, respectively, that are most promising or have been discussed most widely in the literature. The summary includes the compounds amenable to treatment, the treatment reagents, and the processes.

5.6.3.3 Design and Construction Considerations

Most in situ chemical treatments involve the delivery of a fluid to the subsurface. Therefore, the same

Table 5-21. Summary of In Situ Treatment Methods*

Method	Compounds Amenable to Treatment	Treatment Reagents	Process	Limitations
Precipitation				
Sulfide	Heavy metals	Sodium or calcium sulfide	Forms insoluble metal precipitates.	Carbonate and hydroxide precipitation is effective only over a narrow pH range
Carbonate/ hydroxide	Heavy metals	Lime, calcium carbonate		Soil cations are likely to compete for phosphate
Phosphate	Heavy metals	Superphosphate fertilizer		Potential for release of H_2S gas from sulfide precipitation; precipitation may reduce soil permeability
Oxidation	Trivalent arsenic	Potassium permanganate followed by precipitation with ferrous sulfate, lime, etc.	Oxidizes As (III) to As (V).	Treatment compounds are nonspecific; volatile arsenic may be formed
Reduction	Hexavalent chromium	Ferrous sulfate	Reduces Cr (VI) to Cr (III). Reduces Se (VI) to Se (IV)	Potential for reoxidation of chromium and selenium under certain conditions
Sorption by natural and synthetic materials	Heavy metals	Organic matter, clay, ion exchange materials	Exchanges metals for soil cations or innocuous cations on an ion exchange resin	Potential for release of sorbed metals; ion exchange resins are very costly
Oxidation (organics)	Benzene and substituted benzenes Phenols Halogenated phenols Nitro aromatics PAHs Heterocyclic nitrogen and oxygen compounds Aldehydes and ketones Sulfides, disulfides	Ozone, hypochlorite, or hydrogen peroxide	Increases oxidation state of compounds by loss of electrons; detoxifies compounds or renders them more amenable to biological degradation	Potential for formation of more toxic or soluble degradation products; process is nonspecific, and compounds other than the targeted compounds may be oxidized; use of hypochlorites may result in formation of chlorinated organics; hydrogen peroxide and ozone may decompose rapidly
Reduction (organics)	Nitro aromatics Chlorinated aromatics Chlorinated aliphatics	Catalyzed metal	Decreases oxidation state of compounds by addition of electrons; detoxifies compounds by removal of halogen or nitro group or by saturation of aromatic structure	Treatment reagents may be costly; very limited research has been done on chemical reduction

Table 5-21. (continued)

Method	Compounds Amenable to Treatment	Treatment Reagents	Process	Limitations
Hydrolysis (base-catalyzed)	Esters Amides Carbamates Organophosphorus carbamates Certain pesticides (e.g., parathion, malathion, 2-4D esters, DDT)	Water with lime or NaOH	Nucleophile (e.g., water or hydroxyl ion) attacks an electrophile (e.g., carbon or phosphorous), resulting in bond cleavage and displacement of the leaving group	Sorbed organics may be difficult to hydrolize; very little research has been conducted on the feasibility of in situ hydrolysis
Polymerization	Aliphatic, aromatic, and oxygenated monomers (vinyl chloride, isoprene, acrylonitrile)	Catalyst activation	Converts a compound to a larger chemical multiple of itself	Polymerization results in a decrease in soil permeability; therefore, complex treatment would be difficult to achieve and would require close spacing of injection points; potential for reversal of the polymerization reaction
Sorption by natural and synthetic materials	Hydrophobic organics, organic cations	Sewage, sludge, activated carbon, agricultural products and byproducts, chelates, clay, and ion exchange resins	Complexes, chelates, or sorbs hydrophobic organics by chemical bonding; sorbs cationic organics by ion exchange	Potential for release of sorbed compounds; feasibility and effectiveness is highly site-specific

[*] Data from Wagner and Kosin 1985.

factors that limit the use of injection/extraction wells, drains, or surface gravity application systems (such as flooding and spray irrigation) will limit the applicability of most in situ chemical treatments. Minimal permeability requirements must be met for the treatment solution to be delivered successfully to the contaminated zone. Sandy soils are far more amenable to in situ treatment than clayey soils. In addition, the contaminated ground water must be contained within the treatment zone. Measures must be taken to ensure that treatment reagents do not migrate and become contaminants themselves. Care must be taken during the extraction process not to increase the burden of contaminated water by drawing uncontaminated water into the treatment zone from an aquifer far from hydraulically connected surface waters.

Potential chemical reactions of the treatment reagents with the soils and contaminants must be considered. This form of treatment can reduce the permeability of soils. In soils high in iron and manganese, for example, oxidizing the subsurface could result in precipitation of iron and manganese oxides and hydroxides, which could clog the delivery system and the aquifer.

Mention of potential drawbacks should not preclude consideration of chemical in situ methods; however, laboratory (and possibly pilot-scale) testing probably will be required in each case and delay implementation of the remedial action. As with in situ biological treatment methods, methods used to deliver and recover treatment reagents also affect the reliability of chemical in situ methods.

5.6.3.4 Costs

Costs for chemical in situ treatment approaches are difficult to estimate because, for the most part, these methods have not been demonstrated and no actual cost data are available. In situ treatment costs will be variable, but they could be less than those for excavation and removal methods and/or pumping and treating methods. As with removal, in situ treatment is a one-time effort, so as a rule no long-term operation and maintenance costs would be involved.

Costs for chemical treatments involving the delivery of a reagent to the subsurface will depend on the amount of material to be treated; the amount of chemical reagent required; the costs for the delivery system and the chemical feed system; and fees for probing, excavation, and drilling. Costs for laboratory- and pilot-scale studies also should be considered when evaluating this approach to remediation.

5.6.4 Physical Treatment

5.6.4.1 General Description

Several methods currently under development involve physical manipulation of the subsurface to immobilize or detoxify contaminants. These technologies, which include in situ heating, vitrification, and ground freezing, are in the early stages of development and detailed information is not available. Their application to contamination caused by UST releases will probably be limited.

5.6.4.2 Application/Availability

In situ heating has been proposed as a method for destroying or removing organic contaminants in the subsurface through thermal decomposition, vaporization, and distillation. Steam injection and radio frequency (RF) heating are the recommended heating methods. The radio frequency heating process has been under development since the 1970's, and field experiments have been conducted for the recovery of hydrocarbons. This method involves laying a row of horizontal conductors on the contaminated surface and exciting them with an RF generator through a matching network. The decontamination is accomplished in a temperature range of 300° to 400°C (assisted with steam) and requires a residence time of about 2 weeks. A gas- or vapor-recovery system is required on the surface. No excavation, mining, drilling, or boring is required. Preliminary design and cost estimates for a mobile RF in situ decontamination process indicate that this method is two to four times cheaper than excavation and incineration. The method appears to be very promising for certain situations involving contamination with organics, although more research is necessary to verify its effectiveness.

In situ vitrification, a technology under development for the stabilization of transuranic contaminated wastes, is conceivably applicable to other hazardous wastes. Several laboratory-scale and pilot-scale tests have been conducted, and a full-scale testing system is currently being fabricated. The technology is based on electric melter technology, and the principle of operation is joule heating, which occurs when an electrical current is passed through a molten mass. Contaminated soil is converted into durable glass, and wastes are pyrolyzed or crystallized. Off-gases released during the melting process are trapped in an off-gas hood. The depth of the contamination is a significant limiting factor in the application of this technology; 1 to 1.5 meters of uncontaminated overburden lowers release fractions considerably.

Artificial ground freezing involves the installation of freezing loops in the ground and a self-contained refrigeration system that pumps coolant around the freezing loop. Although this technology has never been used in an actual spill or leak containment operation, its use as a construction method in civil engineering projects is increasing. Artificial ground freezing is not applied to the contaminant itself, which may have a freezing point much lower than that of the soil systems, but to the soil surrounding it. Freezing renders the soil practically impermeable; however, its value is temporary because of the thermal maintenance expense.

5.6.4.3 Design and Construction Consideration

The techniques discussed in this subsection (in situ heating, vitrification, and ground freezing) are in the early stages of development. Therefore, detailed design and construction considerations are not available.

5.6.4.4 Costs

No actual cost figures are available for these technologies because they are still in the developmental stage. Some estimated costs are presented in Table 5-22.

Table 5-22. Estimated Costs for In Situ Physical Treatment Methods

Technology	Cost Basis	Cost Range
Radio frequency heating	Estimate for hypothetical 1-acre area contaminated to a depth of 20 ft	\$5 to \$6 million (operating costs only)
Vitrification	Estimate for a site contaminated to a depth of 13 ft	\$200 to \$280/yd^3
Ground freezing	Estimate for hypothetical 1000 ft x 3 ft x 40 ft deep frozen wall of soil	\$154,000 to \$310,000

5.7 Ground-Water Treatment

Many of the concepts of ground-water treatment, an old science that modern technology has improved, have been developed through years of experience in treating industrial wastewaters. Today's emphasis on correcting contamination problems in diverse locations has prompted new applications of these concepts to remedy extreme situations of ground-water contamination, e.g., a leaking underground petroleum product storage system.

Selection of treatment depends on the contaminants to be removed. A system may consist of a combination of several technologies to effect a solution. Such a combination will result from treatability studies that should be conducted with representative samples. Some of the treatment technologies for ground water that are more applicable to underground storage system leaks are described in this section. These descriptions are intended as background for assembling a system to remedy a particular leak situation based on the treatability study. Table 5-23 lists the treatment processes discussed herein and the contaminants to which they can be applied.

Table 5-23. Applicability of Ground-Water Treatment Processes

Treatment Process	Gasoline and Volatile Organics	Non-Volatile Organics	Inorganics
Air stripping	x		
Carbon adsorption	x	x	
Biological treatment	x	x	
Precipitation/flocculation/ sedimentation			x
Dissolved air flotation			x
Granular media filtration	x*	x*	x
Ion exchange/resin adsorption			x
Oxidation/reduction		x	
Neutralization			x
Steam stripping	x		
Reverse osmosis			x
Sludge dewatering			x

*Pretreatment.

5.7.1 Air Stripping

5.7.1.1 General Description

In an air stripping process, a contaminated water stream is mixed with a clean air stream, and the intimate contact causes the air to remove the dissolved organic substances from the water. The different kinds of equipment used to carry out this process are classified primarily as towers and basins. Basins are usually large installations with floating aerators such as those found in municipal sewage and/or water treatment plants. Towers are more applicable for an UST release because they are readily available. Mobile units can be obtained from vendors and contractors. Only towers are discussed here. Figure 5-31 shows typical air-stripping equipment configurations.

5.7.1.2 Application/Availability

A typical air-stripping tower is similar in construction to a water cooling tower. Contaminated water is fed into the top and flows down over an internal system of baffles or packing designed to spread it out over a large surface. As the water flows down through the tower, a fan moves air up through the tower, where the baffling or packing causes it to come into intimate contact with the water. During the contact, the air picks up dissolved organic substances.

The countercurrent packed tower appears to be the most appropriate equipment configuration for treating contaminated ground waters for the following reasons (Canter and Knox 1986):

1) It provides the most liquid interfacial area.
2) High air-to-water volume ratios are possible because of the low air pressure drop through the tower.
3) Emission of stripped organics to the atmosphere may be environmentally unacceptable; however, a countercurrent tower is relatively small and can be readily connected to vapor-recovery equipment.

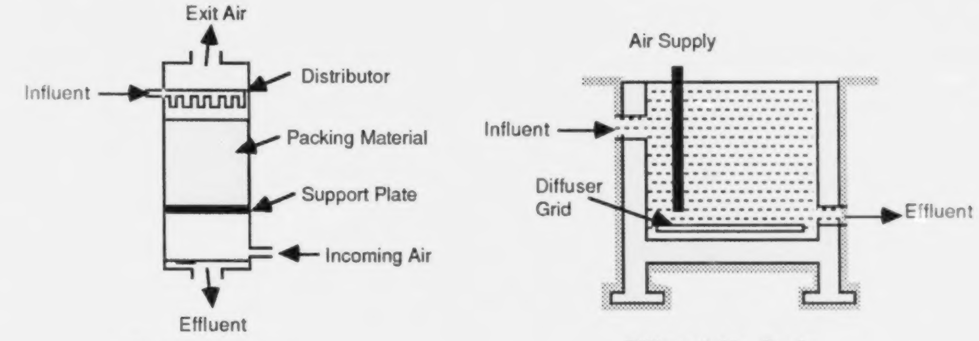
Air stripping has been successful in removing volatile organics from contaminated ground waters. Table 5-24 summarizes removals that have been achieved for various organic contaminants at various air-to-water ratios.

Table 5-24. Packed-Column Air Stripping of Volatile Organics*

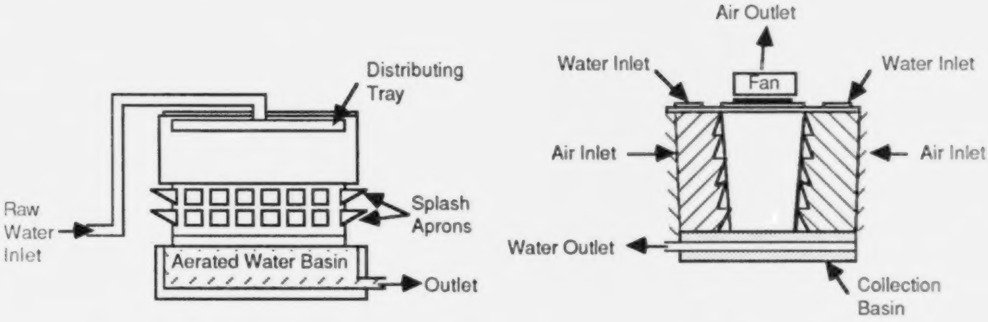
Organic Contaminant	Air-to-Water Ratio	Influent (μg/liter)	Effluent (μg/liter)
1,1,2-Trichloroethylene	9.3	80	16
	96.3	80	3
	27.0	75	16
	156.0	813	52
	44.0	218	40
	75.0	204	36
	125.0	204	27
1,1,1-Trichloroethane	9.3	1200	460
	96.3	1200	49
	27.0	90	31
	156.0	1332	143
1,1-Dichloroethane	9.3	35	9
	96.3	35	1
1,2-Dichloropropane	27.0	50	<5
	146.0	70	5
	156.0	377	52
Chloroform	27.0	50	<2
	146.0	57	2
Diisopropyl ether	44.0	15	7
	75.0	14	6
	125.0	4	4

*Data from Canter and Knox 1986.

Figure 5-31. **Air stripping equipment configurations (Knox et al. 1984).**


Exit Air
Influent
Distributor
Packing Material
Support Plate
Incoming Air
Effluent
Air Supply
Influent
Diffuser Grid
Effluent

Packed Column **Diffused-Air Basin**


Distributing Tray
Raw Water Inlet
Splash Aprons
Aerated Water Basin
Outlet
Air Outlet
Water Inlet
Fan
Water Inlet
Air Inlet
Air Inlet
Water Outlet
Collection Basin

Coke-Tray Aerator **Cross-Flow Tower**

5.7.1.3 Design and Construction Considerations

The design of a process for air stripping volatile organics from contaminated ground water is accomplished in two steps. The first step involves determining the cross-sectional area of the column by using the physical properties of the air flowing through the column, the characteristics of the packing, and the air-to-water flow ratio. A key factor is the establishment of an acceptable air velocity. A general rule of thumb used for establishing the air velocity is that an acceptable air velocity is 60 percent of the air velocity at flooding. Flooding refers to the condition in which the air velocity is so high that it holds up the water in the column to the point where the water becomes the continuous phase rather than the air. If the air-to-water ratio is held constant, the air velocity determines the flooding condition. For a selected air-to-water ratio, the cross-sectional area is determined by dividing the air flow rate by the air velocity. The selection of the design air-to-water ratio must be based on experience or pilot-scale treatability studies. Treatability studies are particularly important for developing design information for contaminated ground water (Canter and Knox 1986). In the second step, the column height is determined mathematically from the physical properties of the contaminant and the stripping air.

Installation of a unit usually requires field assembly of equipment or placement of shop-fabricated/packaged units. Installation of the complex tower internals is the most labor-intensive task. Overall, however, installation of an air stripper is relatively simple and can be done by most mechanical contractors.

The exiting air stream must be examined to determine if it will be a source of air pollution. If it is, cleanup technologies for vapor recovery can be added to remedy that situation.

Because an air-stripping system is simple to operate and occupies minimal space, it is a prime candidate for treating contaminated ground water at service station sites.

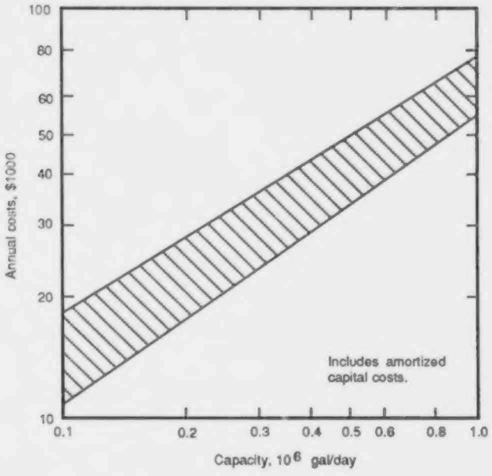
5.7.1.4 Costs

Although variations in the design of packed-column air stripping systems result in varying costs, the major components of an air-stripping system for removing organic contaminants from ground water include the packed column, the air supply equipment, and repumping equipment. Annual costs per 1000 gal of water treated are shown in Table 5-25. Figure 5-32 presents the cost data in a graphic format. The costs are from 1982 and have been updated to 1986 using the Engineering News Record Construction Index. They are based upon preliminary designs for achieving 90 percent removal of trichloroethylene (TCE).

Table 5-25. Costs for Packed-Column Aeration

Water rate (10^6 gal/day)	Cost per 1000 gal water treated (¢)
0.1	30 to 50
1.0	15 to 20

Figure 5-32. Annual costs for air stripping system.



5.7.2 *Carbon Adsorption*

5.7.2.1 General Description (EPA 1985a)

The process of adsorption onto activated carbon involves contacting a waste stream with the carbon, usually by allowing it to flow through a series of packed-bed reactors. The activated carbon selectively adsorbs organic constituents by a surface attraction phenomenon in which organic molecules are attracted to the internal pores of the carbon granules. These systems are portable skid-mounted devices that can be rapidly deployed, which makes them especially attractive for use in gasoline releases from underground storage tanks.

Adsorption depends on the strength of the molecular attraction between adsorbent and adsorbate, molecular weight, type and characteristic of adsorbent, electrokinetic charge, pH, and surface area.

When the micropore surfaces become saturated with organics, the carbon is "spent" and must either be replaced with virgin carbon or be thermally regenerated and returned to service. The time it takes to reach "breakthrough" or exhaustion is the single most critical operating parameter. Carbon longevity balanced against influent concentration governs operating economics.

Most ground-water treatment applications involve the use of adsorption units that contain granular activated carbon (GAC) and operate in a downflow series mode such as that shown in Figure 5-33.

In general, the downflow fixed-bed series mode has proved to be the most cost-effective and to produce the lowest effluent concentrations relative to other carbon adsorber configurations (e.g., downflow in parallel, moving bed, upflow-expanded). The units may be connected in parallel to increase the hydraulic capacity.

5.7.2.2 Application/Availability (EPA 1985a)

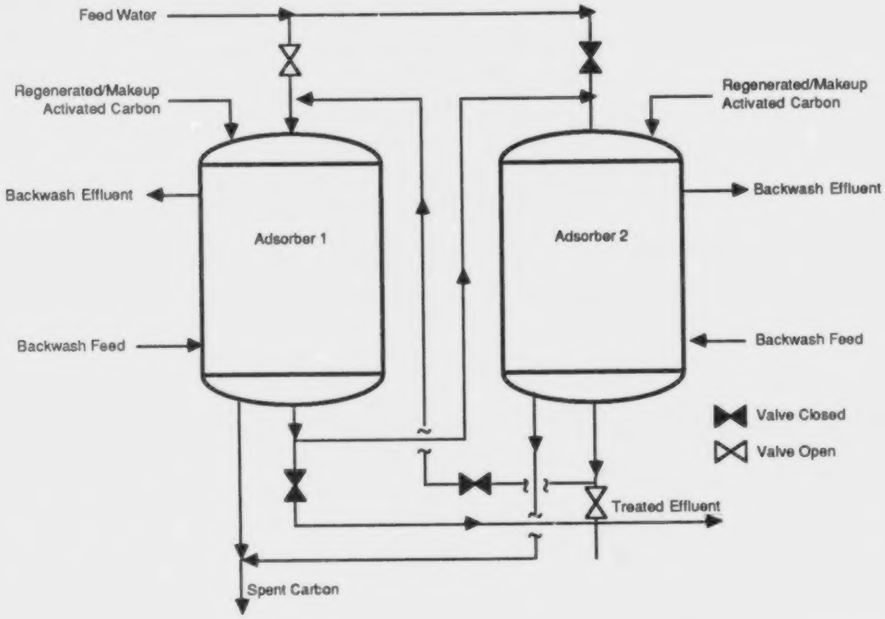
Activated carbon is a well-developed technology that is widely used in the treatment of contaminated ground water. It is especially well suited for removal of mixed organics from contaminated ground water.

Carbon adsorption is essentially an electrical interaction phenomenon; therefore, the polarity of the contaminant compounds will determine its effectiveness to a great extent. Highly polar molecules cannot be removed effectively by carbon adsorption. Another factor that is likely to affect the effectiveness of carbon adsorption is aqueous solubility. The more hydrophobic (insoluble) a molecule is, the more readily the compound is adsorbed. Low-solubility humic and fulvic acids that may be present in the ground water can sorb to the activated carbon more readily than most waste contaminants and result in rapid carbon exhaustion.

Activated carbon is an effective and reliable means of removing low-solubility organics, and it is suitable for treating a wide range of organics of widely varying concentrations. Some metals and inorganic species also have shown excellent to good adsorption potential, including antimony, arsenic, bismuth, chromium, tin, silver, mercury, cobalt, zirconium, chlorine, bromine, and iodine. The highest concentration of solute in the influent stream that has been treated on a continuous basis is 10,000 ppm total organic carbon (TOC), and a 1 percent solution is currently considered as the upper limit (De Renzo 1978).

Adsorption is not particularly sensitive to changes in concentrations or flow rate and, unlike biological treatment, it is not adversely affected by toxics. It is, however, quite sensitive to suspended solids and oil-and-grease concentrations. Thus, pretreatment is required for oil and grease and suspended solids.

Figure 5-33. Two-vessel granular carbon adsorption system (EPA 1979).



Concentrations of oil and grease in the influent should be limited to 10 ppm. Suspended solids should be less than 50 ppm for upflow systems; downflow systems can handle much higher solids loadings.

Activated carbon is easily implemented into more complex treatment systems. The process is well suited to mobile treatment systems as well as to onsite construction. Space requirements are small, startup and shutdown are rapid, and numerous contractors are experienced in the operation of mobile units.

5.7.2.3 Design and Construction Considerations (EPA 1985a)

Carbon adsorption is frequently used following biological treatment and/or granular media filtration. These treatments reduce the organic and suspended solids load on the carbon columns. It is also used to remove refractory organics that cannot be biodegraded. Air stripping also may be applied prior to carbon adsorption to remove a portion of the volatile contaminants and thereby reduce the organic load to the column. These pretreatment steps all minimize carbon regeneration costs.

Like air stripping, carbon adsorption systems are relatively compact and easy to operate. On the other hand, the phenomenon of adsorption is extremely complex and not mathematically predictable. Field pilot-plant studies are necessary for the accurate prediction of the performance, longevity, and operating economics of carbon adsorption. The following data need to be established during pilot-plant testing for an initial estimate of carbon column sizing:

- Hydraulic retention time (hours)
- Flow (gallons/minute)
- Hydraulic capacity of the carbon (gallons waste/pound carbon)
- Collected volume of treated ground water at breakthrough (gallons)
- Carbon density (pounds carbon/cubic foot)

The use of several carbon adsorption columns at a site can provide considerable flexibility. The various columns can be arranged in series to increase service life between regeneration of the lead bed or in parallel for maximum hydraulic capacity. The piping arrangement should allow for one or more beds to be regenerated while the other columns remain in service.

The most obvious maintenance consideration associated with activated carbon treatment is the regeneration of spent carbon for reuse. Regeneration must be performed for each column at the conclusion of its bed-life so the spent carbon can be restored as close as possible to its original condition for reuse; otherwise, the carbon must be disposed of. Other operation and maintenance requirements for the activated carbon technology are minimal if appropriate automatic controls have been installed.

The thermal destruction properties of the contaminant should be determined prior to selection of an activated carbon treatment technology, as any chemicals sorbed to activated carbon must eventually be destroyed in a carbon regeneration furnace. Therefore, of crucial importance in the selection of activated carbon treatment is whether the sorbed contaminant can be effectively destroyed in a regeneration furnace; if not, they will become air pollutants when introduced into the furnace.

The biggest limitation to the use of the activated carbon process is the high capital and operating cost. The operating costs can be substantially reduced by pretreatment of the waste.

5.7.2.4 Costs (EPA 1985a)

The cost of activated carbon units depends on the size of the contact unit, which is influenced by the concentrations of the target and nontarget organic compounds in the ground water and the desired level of target compounds in the effluent. Table 5-26 presents construction, operation, and maintenance costs for cylindrical, pressurized, downflow steel contactors based on a nominal detection time of 17.5 minutes and a carbon loading rate of 5 gal/min per ft^2. The construction costs include housing, concrete foundation, and all the necessary pipes, valves, and nozzles for operating the unit plus the initial change of carbon. The operation and maintenance costs include the electricity and assume carbon replacement once a year; however, systems for unloading spent carbon and loading fresh carbon are not included. Figure 5-34 presents these costs in a graphic format.

Figure 5-34. **Estimated costs of various sizes of Activated Carbon Adsorption Units.**

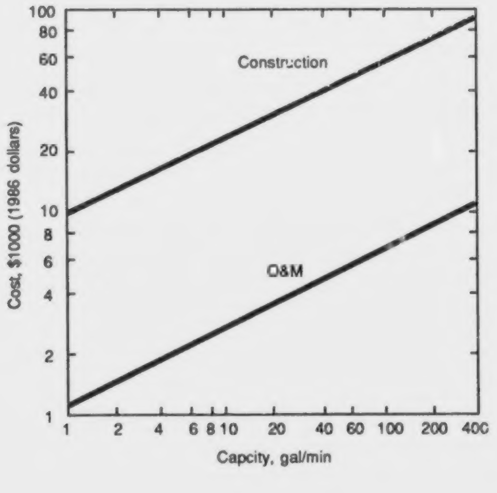


Table 5-26. **General Cost Data for Various Sizes of Activated-Carbon Adsorption Units***

Capacity (gal/min)	Column Diameter (ft)	Column Length (ft)	Housing Area (ft^2)	Construction Costs† ($)	O&M Costs† ($/yr)
1.7	0.67	5	60	12,500	1,720
17	2	5	150	24,200	2,360
70	4	5	300	43,300	4,890
175	6.5	5	375	65,200	8,270
350	9	5	450	95,600	12,70

* Data adapted from Hansen, Gumerman, and Culp 1979.
† Costs were updated from 1979 to 1986 dollars by using the second-quarter Marshall and Swift Equipment Index.

Several manufacturers market mobile activated-carbon-adsorption systems. For example, Calgon Carbon Corporation has a trailer-mounted carbon adsorption treatment unit that can be shipped to a treatment site within 24 to 48 hours. The system can be configured with either single or multiple prepiped adsorber vessels and it can handle a flow of up to 200 gal/min. The following costs are associated with a mobile system consisting of two 10-ft-diameter, 10-ft-high, skid-mounted vessels capable of handling up to 200 gal/min (Calgon Corp., undated):

Delivery, supervision of installation and startup, tests to conduct reactivation of carbon, dismantling and removal of system (including freight to and from the site)	$25,200
Delivery and removal of one truckload of carbon (2000 lb). (Two truckloads of carbon required for a two-vessel system)	$15,300
Rental fee	$5100/month

Calgon Carbon Corporation will take spent carbon back for reactivation. Otherwise, disposal costs for spent carbon must be added.

5.7.3 Biological Treatment

5.7.3.1 General Description

The function of biological treatment is to remove organic matter from the ground water through microbial degradation. The most prevalent form of biological treatment is aerobic, i.e., in the presence of oxygen. Several existing biological treatment processes may be applicable for the treatment of ground water from an UST, including the conventional activated sludge process. Modifications of the activated sludge process include the use of pure oxygen-activated sludge, extended aeration, and contact stabilization; and fixed-film systems, which include rotating biological discs and trickling filters.

In a conventional activated-sludge process, ground water flows into an aeration basin, where it is aerated for several hours. During this time, a suspended active microbial population (maintained by recycling sludge) aerobically degrades organic matter in the stream and produces new cells. A simplified equation for this process is:

$$\text{Organics} + O_2 \rightarrow CO_2 + H_2O + \text{new cells}$$

The new cells produced during aeration form a sludge that is settled out in a clarifier. A portion of the settled sludge is recycled to the aeration basin to maintain the microbial population, and the remaining sludge is wasted (i.e., it undergoes volume reduction and disposal). Clarified water is disposed of or receives further processing.

In the pure oxygen-activated sludge process, oxygen and oxygen-enriched air is used instead of normal air to increase the transfer of oxygen. Extended aeration involves longer detention times than conventional activated sludge and relies on a higher population of microorganisms to degrade contaminants. Contact stabilization involves only short contact of the contaminants and suspended microbial solids; the sludge is then allowed to settle before it is treated to remove sorbed organics. Fixed-film systems involve contact of the contaminants with microorganisms attached to some inert medium such as rock or some specially designed plastic material. The original trickling filter consists of a bed of rocks over which the contaminated water is sprayed. The microbes that form a slime layer on the rocks metabolize the organics, while oxygen (air) moves countercurrently to the water flow (Canter and Knox 1985).

Biological towers are a modification of the trickling filter. The medium [e.g., polyvinyl chloride (PVC), polyethylene, polystyrene, or redwood] is stacked into towers that typically reach 16 to 20 ft. The contaminated water is sprayed across the top, and air is pulled upward through the tower as the water moves downward. A slime layer of microorganisms forms on the media and removes the organic contaminants as the water flows over the slime layer.

A rotating biological contactor (RBC) consists of a series of rotating discs (connected by a shaft) set in a basin or trough. The contaminated water passes through the basin, where the microorganisms attached to the discs metabolize the organics present in the water. Approximately 40 percent of the disc's surface area is submerged. This allows the slime layer to come in contact with the contaminated water and the air alternately, which provides oxygen to the microorganisms (Canter and Knox 1985).

5.7.3.2 Application/Availability

Biological treatment offers considerable flexibility because of the variety of available processes and the adaptability of the microorganisms themselves. Although many organic chemicals are considered biodegradable, the relative ease of biodegradation varies widely. Several generalizations can be made with regard to the ease of treatability of organics by aerobic biological treatment:

- Unsubstituted nonaromatics or cyclic hydrocarbons are preferred over unsubstituted aromatics.
- Materials with unsaturated bonds, such as alkenes, are preferred over those with saturated bonds.
- Soluble organics are usually more readily degraded than insoluble materials. Biological treatment is generally efficient in removing dissolved or colloidal materials, which are more readily attacked by enzymes. This is not the case, however, for fixed-film treatment systems, which preferentially treat suspended matter.
- The presence of functional groups affects biodegradability. Alcohols, aldehydes, acids, esters, amides, and amino acids are more degradable than corresponding alkanes, olefins, ketones, dicarboxylic acids, nitriles, and chloroalkanes.
- Halogen-substituted compounds are the most refractory to biodegradation; chlorinated aliphatics are generally more refractory than the corresponding aromatics. The number of halogens and their position are also significant in determining degradation.
- Nitro-substituted compounds are also difficult to degrade; however, they are generally less refractory than the halogen-substituted compounds.

Several compounds are considered relatively resistant to biological treatment; however, the treatability of waste should be determined through laboratory biological oxygen demand (BOD) tests on a case-by-case basis.

Despite the fact that industrial-type wastes may be refractory to biological treatment, microorganisms can be acclimated to degrade many compounds that are initially refractory. Similarly, whereas heavy metals are inhibitory to biological treatment, the biomass also can be acclimated, within limits, to tolerate elevated concentrations of metals.

Table 5-27 presents the applications and limitations of the available biological treatment processes. The completely mixed activated-sludge process is the most widely used process for treatment of contaminated ground water with relatively high organic loads; however, the high-purity oxygen system has advantages for UST site corrective actions.

Table 5-27. Summary of Applications/Limitations of Biological Treatment Process*

Process	Applications/Limitations
Conventional	Applicable to low-strength wastes; subject to shock loads
Completely mixed conventional	Resistant to shock loads
Extended aeration	Requires low organic load and long detention times; low sludge volume; available as packaged plant
Contact stabilization	Not suitable for soluble BOD
Pure oxygen	Suitable for high-strength wastes; low sludge volume; reduced aeration tank volume
Trickling filters	Most effective for removal of colloidal and suspended BOD; used primarily as a roughing filter
Rotating biological disc	Can handle large flow variations and high organic shock loads; modular construction provides flexibility to meet increased or decreased treatment needs

* Data from EPA 1985a.

Other parameters that may influence the performance of a biological treatment system include concentration of suspended solids, oil and grease; organic load variations; and temperature. Table 5-28 lists the parameters that may affect system performance, their limiting concentrations, and the kind of pretreatment required prior to biological treatment.

Although biological treatment can effectively treat a wide range of organics, it has several drawbacks in UST site applications. The reliability of the process can be adversely affected by shock loads of toxics. Startup time can be slow if the organisms need to be acclimated to the contaminant, and the detention time can be long for complex contaminants. The existence of cultures that have been previously adapted to ground-water contaminants, however, can dramatically decrease startup and detention time.

Several cleanup contractors have used biological treatment as part of a mobile treatment system. The high-purity oxygen treatment process is well suited for mobile treatment applications because the high oxygen efficiency enables use of smaller reactors, a shorter detention time, and less power consumption relative to other activated sludge processes. A hazard associated with the high-purity oxygen process is that the presence of low-flash-point compounds can present a potential fire hazard; however, the system is equipped with hydrocarbon analyzers and control systems that deactivate the system when dangerously high concentrations of volatiles are detected (Ghassemi, Yu, and Quinlivan 1981). Loss of volatile organics from other biological treatment processes also can pose some localized air pollution and a health hazard to field personnel. These systems may be restricted when gasoline is the contaminant of concern.

Rotating biological contactors also have advantages for UST site treatment. These compact units can handle large flow variations and high organic shock loads, and they do not require use of aeration equipment.

Sludge produced in biological ground-water treatment may be a hazardous waste itself because of the sorption and concentration of toxic and hazardous compounds contained in the wastewater. If the sludge is hazardous, it must be disposed of in a RCRA-approved manner. Nonhazardous sludge should be disposed of in accordance with State sludge disposal guidelines.

5.7.3.3 Design and Construction Considerations

Design of the activated sludge or fixed-film systems for a particular application are best achieved by first representing the system as a mathematical model, and then determining the necessary coefficients through laboratory or pilot tests.

The following models have been found to be reliable for use in the design of biological treatment systems for ground water containing priority pollutants (Canter and Knox 1986).

Activated sludge:

$$V = \frac{FS_i/X}{\dfrac{U_{max}\ S_i}{S_i - S_e} - K_B}$$

Biological tower and rotating biological contactor:

$$A = \frac{FS_i}{\dfrac{U_{max}\ S_i}{S_i - S_e} - K_B}$$

where
V = volume of aeration tank, ft^3
F = flow rate, ft^3/day
X = mixed liquor volatile solids, mg/liter

S_i = influent BOD, COD, TOC, or specific organics, mg/liter

Table 5-28. **Concentration of Pollutants That Make Prebiological or Primary Treatment Advisable***

Pollutant or System Condition	Limiting Concentration	Kind of Treatment
Suspended solids	>50 to 125 mg/liter	Sedimentation, flotation, or lagooning
Oil or grease	>35 to 50 mg/liter	Skimming tank or separator
Toxic ions		Precipitation or ion exchange
Pb	≤0.1 mg/liter	
Cu + Ni + CN	≤1 mg/liter	
Cr^{+6} + Zn	≤3 mg/liter	
Cr^{+3}	≤10 mg/liter	
pH	<6, >9	Neutralization
Alkalinity	0.5 lb alkalinity as $CaCO_3$/lb BOD removed	Neutralization for excessive alkalinity
Acidity	Free mineral acidity	Neutralization
Organic load variation	>2:1 to 4:1	Equalization
Sulfides	>100 mg/liter	Precipitation or stripping with recovery
Phenols	>70 to 300 mg/liter	Extraction, adsorption, or internal dilution
Ammonia	>1.6 g/liter	Dilution, ion exchange, pH adjustment, or stripping
Dissolved salts	>10 to 16 g/liter	Dilution or ion exchange
Temperature	13° to 38°C in reactor	Cooling or steam addition

* Data from Conway and Ross 1980.

S_e = effluent BOD, COD, TOC, or specific organics, mg/liter

U_{max} and K_B = biokinetic constants, day^{-1}

A = surface area of biological tower or rotating biological contactor, ft^2

After the biokinetic constants are determined by conducting laboratory or pilot-plant studies, the required volume of the aeration tank or the required surface area for a biological tower or rotating biological contactor can be determined for any flow rate; the influent concentration of BOD, COD, TOC, or specific organic; and the required effluent concentration of BOD, COD, TOC, or specific organic.

The design approaches of conventional, completely mixed, activated sludge systems are well established. The considerations are rate-limiting and establish the size of the reaction basin and sludge settling zone (i.e., the solids settling rate and the BOD and organic removal rates).

Biologically degradable organics can be in solution or in the form of a particulate solid. Only soluble organics can be absorbed and metabolized by activated sludge microorganisms. The rate of metabolism is a function of time, the concentration gradient, and toxicity. Solid degradable organics are removed by adsorption on the activated sludge microorganisms. A relationship between the sludge retention time and the biodegradable fraction remaining can be established for any given waste. To reproduce and function properly, the microorganisms must have a source of energy, carbon, and nutrients. The addition of phosphoric acid to the wastewater is usually necessary to maintain a proper carbon/nutrient ratio for biooxidation. The effluent values of biodegradable pollutants may be calculated by the following formula:

$$S_e = S_o/[1 + (K_p)(MLVSS)(HRT)]$$

where S_e = effluent pollutant, mg/liter

S_o = influent pollutant, mg/liter

K_p = average pollutant removal rate coefficient for specified temperature, hour^{-1}

MLVSS = mixed liquor volatile suspended solids, mg/liter

HRT = hydraulic retention time, hours

As the equation indicates, the longer it takes the microorganisms to metabolize a given pollutant, the higher the MLVSS required or the longer the hydraulic retention time needed to reach the effluent limitations.

Solids (sludge) removal and disposal depend largely on the efficiency of the solid/liquid separation phase of the treatment system. Solids will accumulate in the activated sludge system unless a portion is wasted. This accumulation results from 1) the removal of inert materials, and 2) production of cellular material through microorganism synthesis. Because clarifier (sedimentation) efficiency is related both to its overflow rate and to the settling velocity of the sludge entering it, the separation system is usually designed for peak flow conditions.

5.7.3.4 Costs

Costs of various sizes of activated sludge units are presented in Table 5-29. The costs for these units assume a detention time of 3 hours and the use of aeration basins, air-supply equipment, piping, and a blower building. Clarifier and recycle pumps are not included. The basins are sized to 50 percent recycle flow. The influent BOD is assumed to be no greater than 130 ppm, and the effluent BOD is assumed to be 40 ppm.

Table 5-29. General Cost Data for Various Sizes of Activated SludgeTreatment Units*

Capacity (gal/min)	Construction Costs† ($)	O&M Costs† ($/yr)
70	79,300	4,400
140	86,500	6,600
350	108,000	10,200
694	162,000	16,000

* Data adapted from EPA 1980.

† Costs were updated from 1978 to 1986 dollars by using the second-quarter Marshall and Swift Equipment Index.

The operation and maintenance costs assume that the hydraulic head loss through the aeration tank is negligible. Sludge wasting and pumping energy are not included.

Union Carbide manufactures a high-purity-oxygen-activated sludge system (UNOX) suitable for mobile system applications. The mobile UNOX systems have a hydraulic capacity of 5 to 40 gal/min, are contained within 40-ft van trailers, and include an external clarifier. The oxygen required is also supplied by Union Carbide. The customer is expected to provide installation labor, operating manpower, analytical support, and utilities. A typical installation requires 3 or 4 days (Ghassemi, Yu, and Quinlivan 1981).

The mobile UNOX system can be rented or purchased from the Union Carbide Corporation. Estimated rental costs are as follows:

- $6600 for the checkout and refurbishment of equipment to make it operational
- $560/day for onsite service, including engineering consultation on program planning and execution
- $10/day for rental of equipment

- Transportation charges to get the equipment from the manufacturer to the site of operation and back again.

The purchase price of a UNOX mobile unit is between $262,000 and $333,000 (Ghassemi, Yu, and Quinlivan 1981, updated using 1986 second-quarter Marshall Swift Index).

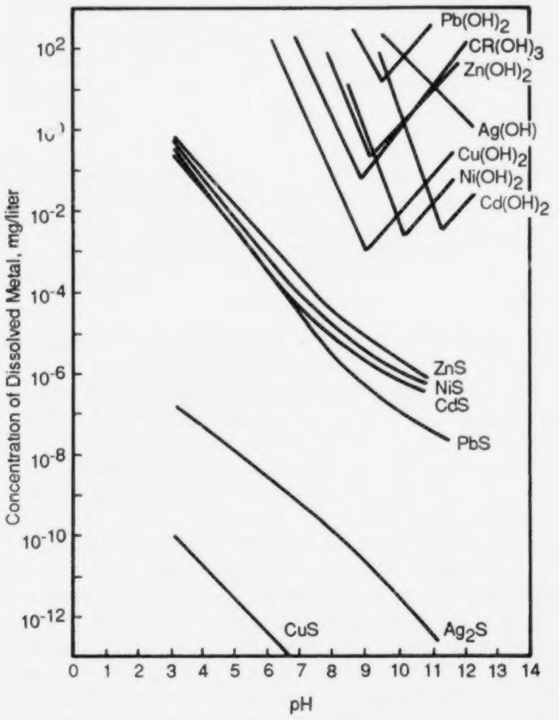
5.7.4 Precipitation/Flocculation/Sedimentation

5.7.4.1 General Description

Precipitation is a physiochemical process whereby some or all of a substance in solution is transformed into a solid phase. The process is based on alteration of the chemical equilibrium relationships affecting the solubility of inorganic species. Removal of metals as hydroxides or sulfides is the most common precipitation application in ground-water treatment. Generally, lime or sodium sulfide is added to the contaminated ground water in a rapid-mix tank along with flocculating agents. The contaminated ground water flows to a flocculation chamber in which adequate mixing and retention time is provided for agglomeration of precipitate particles. Agglomerated particles are separated from the liquid phase by settling in a sedimentation chamber and/or by other physical processes, such as filtration. Figure 5-35 illustrates a typical configuration for the precipitation, flocculation, and sedimentation processes.

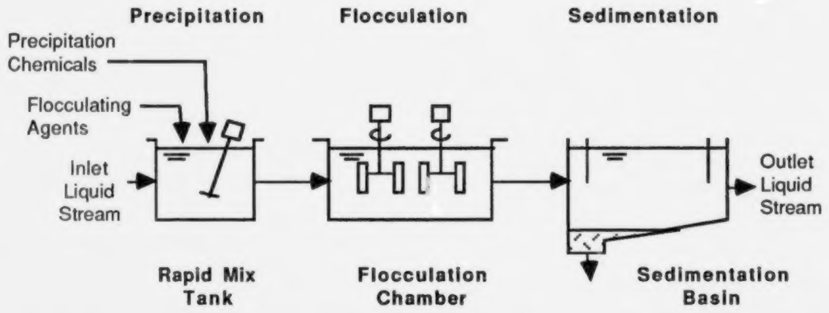
Although precipitation of metals is governed by the solubility product of ionic species, in practice, effluent concentrations equal to the solubility product are rarely achieved. Because of the common ion effect, the amount of lime added is usually about three times the stoichiometric amount that would be added to reduce solubility. Figure 5-36 gives solubilities of various metal hydroxides and sulfides at various pH levels. The metal sulfides have significantly lower solubility than their hydroxide counterparts, and more complete precipitation is achieved. Metal sulfides are also stable over a broad pH range. Many metal hydroxides, on the other hand, are stable only over a narrow pH range; metals reach a minimum solubility at a specific pH, but further addition of lime causes the metal to become soluble again. Therefore, accurate control of lime dosages is needed.

Figure 5-36. **Solubility of metal hydroxides and sulfides (Ghassemi, Yu, and Quinlivan).**



Flocculation refers to the process by which small, unsettleable particles suspended in a liquid medium are made to agglomerate into larger, more settleable

Figure 5-35. **Representative configuration employing precipitation, floccculation, and sedimentation (DeRenzo 1978).**



particles. The mechanisms by which flocculation occurs involve surface chemistry and particle change phenomena. In simple terms, these various phenomena can be grouped into two sequential mechanisms (Kiang and Metry 1982):

- Chemically induced destabilization of the requisite surface-related forces, which allows particles to stick together when they touch
- Chemical bridging and physical enmeshment between the now nonrepelling particles, which allows for the formation of large particles

Flocculation involves three basic steps: 1) addition of the flocculation agent to the waste stream, 2) rapid mixing to disperse the flocculating agent, and 3) slow and gentle mixing to allow for contact between small particles. Typically, chemicals used to promote flocculation include alum, lime, various iron salts (ferric chloride, ferrous sulfate), and organic flocculating agents, often referred to as "polyelectrolytes." These materials generally consist of long-chain, water-soluble polymers such as polyacrylamides. They are used either in conjunction with the inorganic flocculants (such as alum) or as the primary flocculating agent. A polyelectrolyte may be termed cationic, anionic, or ampholytic (depending on the type of ionizable groups), or nonionic if it contains no ionizable groups. The range of physical/chemical characteristics (e.g., density, viscosity, toxicity, and molecular weight) of the several thousand available polymers is extremely broad.

The inorganic flocculants (such as alum, lime, or iron salts) make use of precipitation reactions. Alum (hydrated aluminum sulfate) is typically added to aqueous waste streams as a solution. Upon mixing, the slightly higher pH of the water causes the alum to hydrolyze and form fluffy, gelatinous precipitates of aluminum hydroxide. These precipitates, partially because of their large surface area, enmesh small particles and thereby create larger particles. Lime and iron salts also have a tendency to form large fluffy precipitates or "floc" particles. Many precipitation reactions, such as the precipitation of metals from solution by the addition of sulfide ions, do not readily form floc particles; rather, they precipitate as very fine and relatively stable colloidal particles. In such cases, flocculating agents such as alum and/or polyelectrolytes must be added to cause flocculation of the metal sulfide precipitates (Canter and Knox 1985).

After suspended particles have been flocculated into larger particles, they usually can be removed from the liquid by sedimentation, if a sufficient density difference exists between the suspended matter and the liquid.

Sedimentation relies on gravity to remove suspended solids. The fundamentals of a sedimentation process include (Kiang and Metry 1982):

- A basin or container of sufficient size to maintain the liquid to be treated in a relatively quiescent state for a specified period of time
- A means of directing the liquid to be treated into the basin mentioned above in a manner conducive to settling
- A means of physically removing the settled particles from the liquid (or liquid from the settled particles)

Sedimentation can be carried out either as a batch or as a continuous process in lined impoundments, conventional settling basins, clarifiers, and high-rate gravity settlers. Modified above-ground swimming pools often have been used for sedimentation in temporary, short-term treatment systems at hazardous waste sites. Figure 5-37 shows three different design configurations for sedimentation. In sedimentation ponds, the liquid is merely decanted as the particles accumulate on the bottom of the pond. Backhoes, draglines, or siphons are used periodically to remove settled solids. Sedimentation basins and clarifiers usually include a built-in solids collection and removal device such as a sludge scraper and draw-off mechanism. Sedimentation basins are generally rectangular, normally use a belt-like collection mechanism, and are used primarily for removal of truly settleable particles from liquid.

Clarifiers are normally circular and are used in applications involving precipitation and flocculation as well as sedimentation. Many clarifiers are equipped with separate zones for chemical mixing and precipitation, flocculation, and sedimentation (Kiang and Metry 1982).

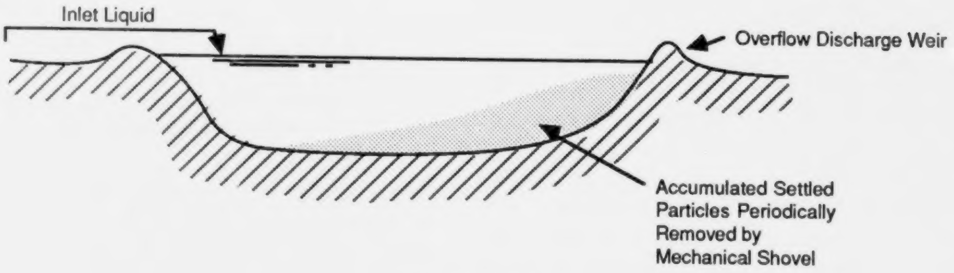
5.7.4.2 Application/Availability

Precipitation is applicable for removal of most metals from ground water, including zinc, cadmium, chromium, copper, fluoride, lead, manganese, and mercury. Certain anionic species (such as phosphate, sulfate, and fluoride) also can be removed by precipitation. Although precipitation is useful for most contaminated ground-water streams, limitations may be imposed by certain physical or chemical characteristics. In some cases, organic compounds may form organometallic complexes with metals that could inhibit precipitation. Cyanide and other ions in the ground water also may complex with metals, and make treatment by precipitation less efficient.

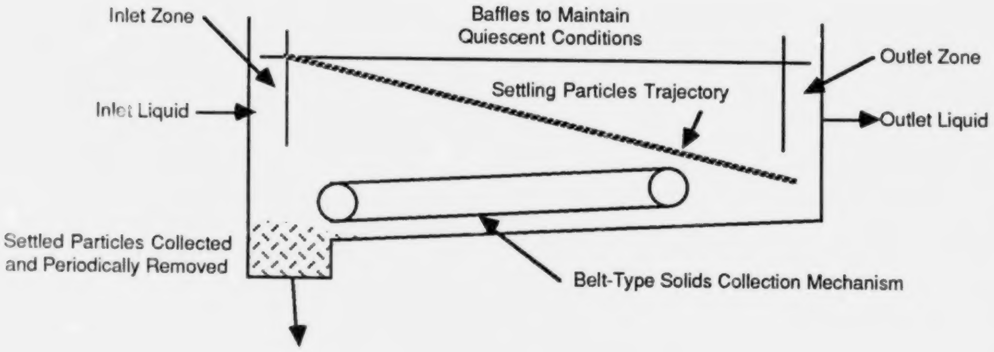
Flocculation is applicable where particles must be agglomerated into larger more settleable particles prior to sedimentation or other types of treatment. There is no concentration limit for precipitation or flocculation.

Sedimentation is commonly applied whenever high suspended solid loadings are encountered. Sedimentation is also required as a pretreatment step for many chemical processes, including carbon ad-

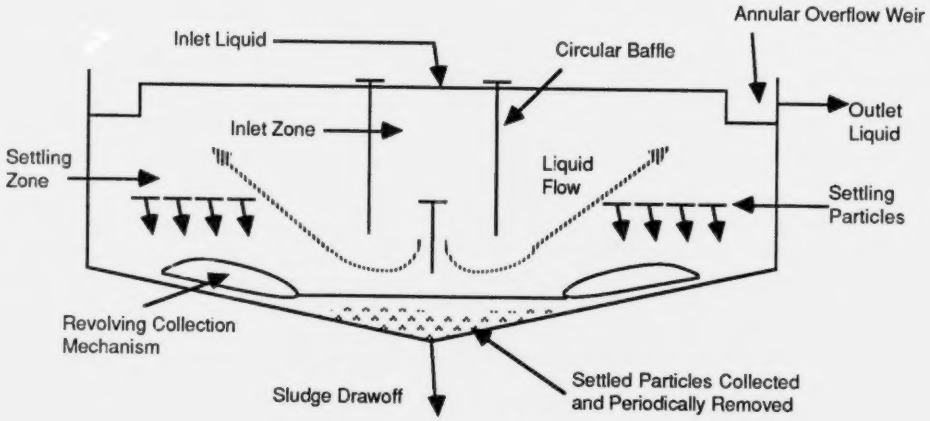
Figure 5-37. **Representative types of sedimentation (DeRenzo 1978).**


Inlet Liquid
Overflow Discharge Weir
Accumulated Settled Particles Periodically Removed by Mechanical Shovel

Settling Pond


Inlet Zone
Baffles to Maintain Quiescent Conditions
Outlet Zone
Settling Particles Trajectory
Inlet Liquid
Outlet Liquid
Settled Particles Collected and Periodically Removed
Belt-Type Solids Collection Mechanism

Sedimentation Basin


Annular Overflow Weir
Inlet Liquid
Circular Baffle
Outlet Liquid
Inlet Zone
Settling Zone
Liquid Flow
Settling Particles
Revolving Collection Mechanism
Sludge Drawoff
Settled Particles Collected and Periodically Removed

Circular Clarifier

sorption, ion exchange, air stripping, reverse osmosis, and filtration. This technology is applicable to the removal of suspended solids heavier than water. Suspended oil droplets or oil-soaked particles may not settle out and have to be removed by some other means. Some sedimentation units are fitted with skimmers to remove oil and grease that float to the water surface; however, these would not be effective in removing emulsified oils.

5.7.4.3 Design and Construction Considerations

Selection of the most suitable precipitate or flocculant and their optimum dosages are determined through laboratory-jar test studies. In addition to determining the appropriate chemicals and optimum chemical dosages, the following important parameters need to be determined as part of the overall design (Canter and Knox 1985):

- Most suitable chemical addition system
- Optimum pH requirement
- Rapid mix requirements
- Sludge production
- Sludge flocculation, settling, and dewatering characteristics

The system is relatively simple. The process requires only chemical pumps, metering devices, and mixing and settling tanks, all of which are readily available and easy to operate. Precipitation and flocculation can be easily integrated into more complex treatment systems, and they pose minimal safety and health hazards to field workers. The entire system is operated at near ambient conditions, which eliminates the danger of high-pressure/high-temperature operations. The chemicals employed are often skin irritants, but they can easily be handled in a safe manner.

Sedimentation is frequently considered in terms of ideal settling. The ideal settling theory results in the following equation for surface loading or overflow rate:

$$V_o = \frac{Q}{A}$$

where V_o = settling velocity
Q = flow through the basin
A = surface area of the basin

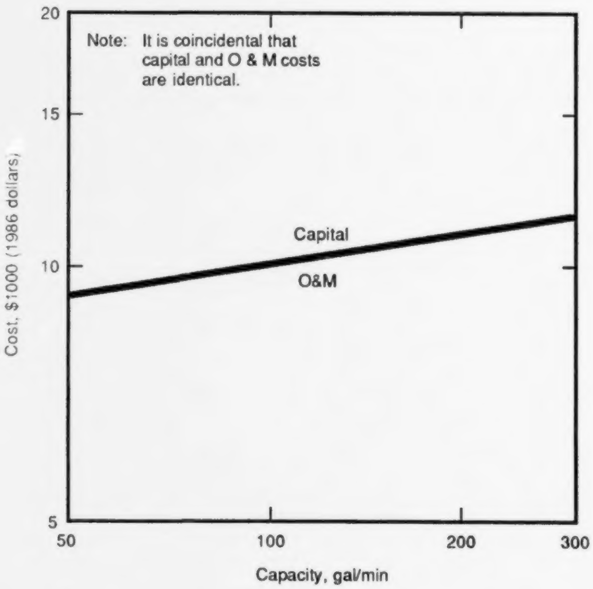
Sedimentation basin loadings are often expressed in terms of gallons per day per square foot. Thus, under ideal settling conditions, sedimentation is independent of basin depth and detention time and depends only on the flow rate, basin surface area, and properties of the particle. In reality, however, sedimentation does not perform according to ideal settling conditions because settling is affected by such conditions as turbulence and bottom scour. Therefore, removal of particles actually does depend on basin depth and detention time as well as flow rate, surface area, and particle size. The performance of a sedimentation basin on suspended discrete particles can be calculated, but it is impossible to calculate sedimentation basin performance on suspended flocculating particles (such as in wastewater) because settling velocities change continually. Laboratory settling tests, however, can be used to predict sedimentation basin performance.

Sedimentation provides a reliable means of removing suspended matter from ground water, if the suspended matter is settleable and the treatment process (including the use of flocculants/coagulants) has been appropriately designed from laboratory settling tests. Most clarifiers are capable of removing 90 to 99 percent of the suspended solids. The process is somewhat space-intensive, however, and its use may be limited by the available space at the site.

5.7.4.4 Costs

Figure 5-38 shows capital and operating costs for a flocculation system, including chemical storage, chemical feeding, and rapid mix. A polymer dosage of 1 mg/liter at 0.25 percent solution is assumed.

Figure 5-38. **Capital and annual O&M costs for flocculation (U.S. EPA 1982).**



Construction costs include piping and a building to house the feeding equipment and bag storage. For a 1000 gal/day or smaller plant, feeding is done manually. Costs include two systems of tanks and feeders. For a 10,000 gal/day plant, the cost includes two solution feeders and mix tanks. For a 100,000 gal/day plant, costs include four feeders and mixing tanks, two holding tanks, and ten solution feeders. The rapid-mix tank is concrete and is equipped with a stainless steel mixer and handrails. No separate building is required for a 100 gal/day plant. Operation of the feeder, mix tank, solution, and holding tank is manual.

5.7.5 Dissolved Air Flotation

5.7.5.1 General Description

In dissolved air flotation (DAF), highly-pressurized air forms bubbles that remove suspended solids. A portion or all of the ground-water feed or a portion of recycled effluent is saturated with air at a pressure of 25 to 70 lb/in.^{2} (gauge). The ground water is held at this pressure for 0.5 to 3.0 minutes in a retention tank and then released to the flotation chamber. The sudden reduction in pressure results in the release of microscopic air bubbles in the flotation chamber, which attach themselves to oil and suspended particles in the ground water. This results in agglomeration that, because of the entrained air, results in greatly increased vertical rise rates of about 0.5 to 2.0 ft/min. The floated materials rise to the surface to form a froth layer, which is continually removed by specially designed flight scrapers or other skimming devices. The retention time in the flotation chamber is usually about 20 to 60 minutes. The effectiveness of dissolved air flotation depends on the attachment of the bubbles to the suspended oil and other particles that are to be removed from the contaminated ground water. The attraction between the air bubble and particle results primarily from the particle surface charges and bubble-size distribution. The more uniform the distribution of water and microbubbles, the shallower the flotation unit can be. Generally, the depth of effective flotation units is between 4 and 9 feet.

In certain cases, the surface sludge layer can attain a thickness of many inches and remain relatively stable for a short period. The layer thickens with time, but undue delays in removal will cause a release of particulates back into the liquid.

Equipment normally associated with an air gas flotation system includes dissolved air flotation units, air compressors, and skimmers. A flow diagram of an air flotation system is shown in Figure 5-39.

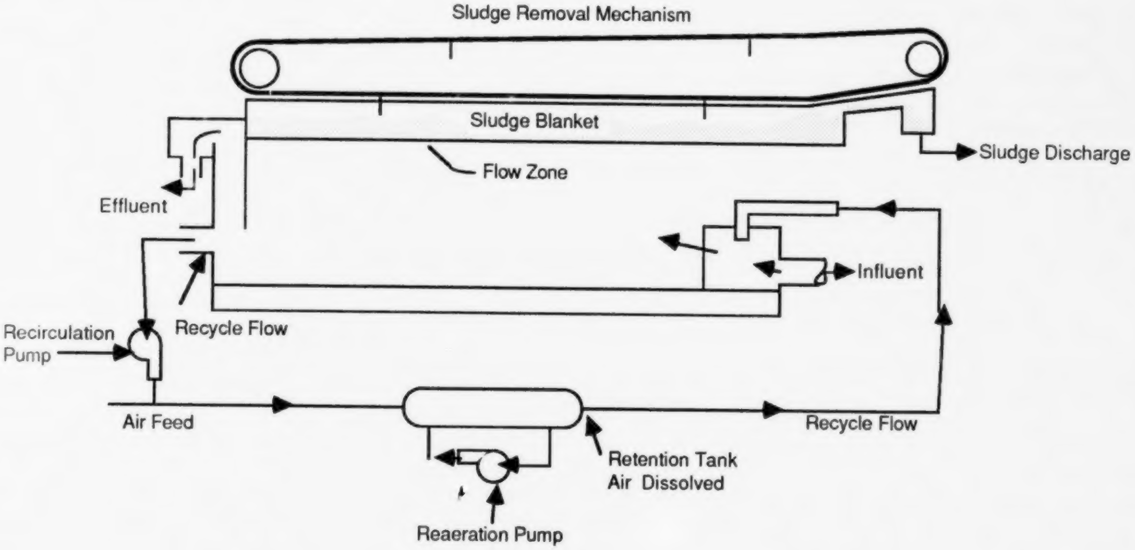
5.7.5.2 Application/Availability

A DAF system is used to remove lighter suspended materials whose specific gravity is only slightly in excess of 1.0. They normally are used to remove oil and grease, but they are sometimes used when existing clarifiers are overloaded hydraulically because converting to DAF requires less surface area.

Used for many years to treat industrial wastewaters, DAF also is commonly used to thicken sludges, including those generated by municipal wastewater treatment. It is not widely used to treat municipal wastewaters, however. Significantly modified systems use pressurized raw waste and pressurized recycle. In addition, gases other than air can be used. For example, the petroleum industry has used nitrogen, with closed vessels, to reduce the possibilities of fire.

Although proven to be reliable, DAF units are subject to variable influent conditions that result in widely

Figure 5-39. Dissolved air flotation system (EPA 1980).



varying performance. Very little use of land is required, and air released from the unit is unlikely to contain volatile organic material.

Chemicals are normally added to aid in the coagulation of colloidal solids and to break emulsions. Such chemical additions include alum, ferric chloride ($FeCl_3$), lime, and polymer, which can be added prior to the actual flotation step.

5.7.5.3 Design and Construction Considerations

Typical design criteria for gas flotation systems are as follows:

Design criterion	Value
Pressure	25 to 70 psig
Air-to-solids ratio	0.01 to 0.1 lb/lb
Float detention	20 to 60 min
Surface hydraulic loading	500 to 8000 gal/day per ft^2
Recycle (where employed)	5 to 120 percent
Solids loading	0.5 to 5 lb/ft^2 per hour

Typical design criteria for dissolved air flotation with chemical addition of alum, $FeCl_3$, lime, and polymers are as follows:

1) Alum addition is determined by jar testing and generally is 5 to 20 mg/liter as aluminum.
2) Ferric chloride addition is determined by jar testing and 20 to 100 mg/liter is common.
3) Typical lime additions are shown below:

Feed water alkalinity (mg/liter) (as $CaCO_3$)	pH	Approximate lime addition (mg/liter) (as CaO)
300	9.5	185
300	10.5	270
400	9.5	230
400	10.5	380

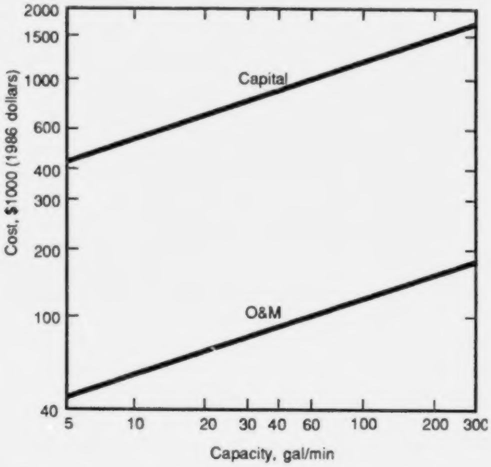
4) Polymer addition is determined by jar testing. The materials contacting polymer solutions should be Type 316 stainless steel, FRP, or plastic. The solutions should be stored in a cool and dry place, and storage time should be minimal. Viscosity must be considered in the feeding system design.

The materials of construction of the chemical feed equipment, chemical storage area, and mixers require special attention because of the corrosive nature of the materials handled. Stainless steel or other corrosion-resistant materials should be selected, depending on each application.

5.7.5.4 Costs

Figure 5-40 indicates the total capital and annual operating costs for dissolved air flotation systems.

Figure 5-40. Capital and annual O&M costs for dissolved air flotation.



The cost estimates assume the following design characteristics:

Operating characteristic	Assumed value
Air injection	1.25 ft^3/1000 gal
Recycle	33 percent
Float detention time	25 min
Surface hydraulic loading	500 to 8000 gal/day per ft^2

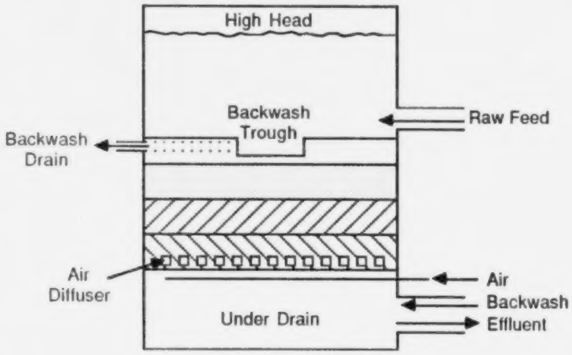
Capital costs and annual operating costs will be greater for air flotation with chemical addition than for air flotation alone because of the required additional equipment, installation, and chemical costs. The additional equipment includes chemical feed equipment, a rapid-mix tank, a chemical storage facility, and a stainless steel mixer. Specific chemical addition capital and operating cost data can be found in the Treatability Manual, Volume IV. Cost Estimating (EPA 600/8-80-042d, July 1980).

5.7.6 Granular Media Filtration

5.7.6.1 General Description

Granular media filtration of contaminated ground water is a physical process whereby suspended solids and colloidal impurities are removed from solution by forcing the liquid through a porous granular medium. The filter media consists of a fixed bed of granular particles (typically sand or sand with finely ground anthracite) (Figure 5-41). The bed is contained within a basin and is supported by an underlain system (typically perforated pipes) that allows the filtered liquid to be drawn off while the filter media is retained in place. The bed may be operated under a typical hydraulic head of 2 to 4 ft of water, or the entire basin may be enclosed and operated under higher

Figure 5-41. Example granular media filtration bed.



pressures. As water laden with suspended solids passes through the media bed, the particles become trapped on top of and within the bed. As the bed becomes loaded with solids, the filtration rate decreases as a result of increased pressure drop through the bed. Plugging is prevented by intermittently backflushing the filter with water at high velocity to dislodge the particles. The backwash water must be treated further because it contains high concentrations of solids (De Renzo 1978). The backwash system may be supplemented with an air-diffusion system.

5.7.6.2 Application/Availability

Granular media filtration can be used to handle ground water containing less than about 200 mg/liter suspended solids, depending on the required effluent level. Greater suspended solids loading will reduce run lengths and require excessively frequent backwashing (De Renzo 1978). The suspended solids concentration of the effluent depends largely on particle size distribution, but granular media filters usually are capable of producing a filtered liquid with a suspended solids concentration as low as 1 to 10 mg/liter. Large flow variations have a deleterious effect on effluent quality.

Granular media filters are often preceded by sedimentation to reduce the suspended solids load on the filter (De Renzo 1978). Granular media filtration also is frequently installed ahead of biological or activated carbon treatment units to reduce the suspended solids load and, in the case of activated carbon, to minimize plugging of the carbon columns (De Renzo 1978).

The granular media filtration process is only marginally effective in treating colloidal-size particles. These particles often can be made larger by flocculation, but this generally reduces run lengths. When such particles cannot be flocculated (as in the case of many oil/water emulsions), more advanced techniques (e.g., ultrafiltration) may be appropriate (De Renzo 1978).

5.7.6.3 Design and Construction Considerations

The composition and sizing of the filtration bed is an important design consideration. Beds frequently used are as deep as 4 ft and composed of sand with a size distribution of about 10 percent less than 0.5 mm and 90 percent less than 1 mm (U.S. EPA 1985a). Sand may be mixed with slightly larger sized anthracite, and the entire bed may be supported on 3/4- to 1/2-in. gravel on the underdrain system; however, deep-bed filters are also available. It is recommended that pilot-plant studies be conducted to determine the optimum size and combination of filter material, filtering rates, and filtering schedule.

A filter bed can function properly only if the backwashing system is effective in cleaning the material from the filter. Methods that can be used for backwashing include water backwash alone, water backwash with auxiliary surface-water wash, water wash preceded by air scour, and simultaneous air and water wash.

The backwash cycle is usually automated, and the duration of the backwash is about 20 minutes per cycle. Backwash water, which amounts to 1 to 5 percent of the total flow, can then be routed to a clarifier via a storage vessel to allow flow equalization. Several filters may be used in parallel to allow continuous processing during backwashing.

Filtration is a reliable and effective means of removing low levels of solids from wastes if the solids content does not vary greatly and the filter is backwashed at appropriate intervals. Filtration equipment is relatively simple, readily available in a wide range of sizes, and easy to operate and control. Filtration is also easily integrated with other treatment steps.

Because of its small space requirements and relatively simple operation, filtration is well suited for mobile treatment systems as well as onsite construction. Granular media filters have been used extensively at hazardous waste sites.

The EPA physical/chemical treatment system, which has been in operation for more than 9 years, incorporates three "dual" media (sand-anthracite) filters connected in parallel in its treatment train. The filters are designed for a maximum hydraulic loading of 7 gal/min per ft^2 or 67 gal/min (Ghassemi, Yu, and Quinlivan 1981). Also, several manufacturers produce packaged plant systems suitable for trailer mounting.

The most obvious maintenance consideration with granular media filtration is the handling of the backwash, which generally will contain high concentrations of contaminants and require subsequent treatment.

5.7.6.4 Costs

Capital costs for relatively small granular media filters with capacities of about 300 gal/min are not readily available. These costs would vary with the construction materials, depth of media, and filtration rate. The approximate capital cost for small, open, coarse-media filters is $400/ft^2 of surface area.* Operation costs include electricity to pump the feed and effluent streams, treatment chemical, if any, and filter media replacement.

5.7.7 Ion Exchange/Resin Adsorption

5.7.7.1 General Description

Ion exchange is a process whereby the toxic ions are removed from the aqueous phase by being exchanged with relatively harmless ions held by the ion exchange material. Modern ion exchange resins are primarily synthetic organic materials that contain ionic functional groups to which exchangeable ions are attached.

These synthetic resins are structurally stable (i.e., they can tolerate a range of temperature and pH conditions), exhibit a high exchange capacity, and can be tailored to show selectivity toward specific ions. Exchangers with negatively charged sites are cation exchangers because they take up positively charged ions. Anion exchangers have positively charged sites and therefore take up negative ions. The exchange reaction is reversible and concentration-dependent, and it is possible to regenerate the exchange resins for reuse. Sorptive (macroporous) resins are also available for removal of organics, and the removal mechanism is one of sorption rather than ion exchange (Ghassemi, Yu, and Quinlivan 1981).

5.7.7.2 Application/Availability

Ion exchange is used to remove a broad range of ionic species from water, including:

- All metallic elements when present as soluble species, either anionic or cationic.
- Inorganic anions such as halides, sulfates, nitrates, and cyanides.
- Organic acids such as carboxylics, sulfonics, and some phenols at a pH sufficiently alkaline to form the ions.
- Organic amines when the solution acidity is sufficiently acid to form the corresponding acid salt (De Renzo 1978).

Sorptive resins can remove a wide range of polar and nonpolar organics.

A practical upper concentration limit for ion exchange is about 2500 to 4000 mg/liter. A higher concentration results in rapid exhaustion of the resin and inordinately high regeneration costs. Suspended solids in the feed stream should be less than 50 mg/liter to prevent plugging the resins, and waste streams must be free of oxidants (De Renzo 1978).

5.7.7.3 Design and Construction Considerations

Specific ion exchange and sorptive resin systems must be designed on a case-by-case basis. Of the three major operating models (fixed-bed cocurrent, fixed-bed countercurrent, and continuous countercurrent), fixed-bed countercurrent systems are the most widely used. Figure 5-42 illustrates the fixed-bed countercurrent and continuous countercurrent systems. The continuous countercurrent system is suitable for high flows. Complete removal of cations and anions (demineralization) can be accomplished by using the hydrogen form of a cation exchange resin and the hydroxide form of an anion exchange resin. For removal of organics as well as inorganics, a combination adsorptive/demineralization system can be used. In this system, lead beds carry sorptive resins that act as organic scavengers, and the end beds contain anion and cation exchange resins. The use of different types of adsorptive resins (e.g., polar and nonpolar) permits removal of a broad spectrum of organics (Ghassemi, Yu, and Quinlivan 1981).

Ion exchange is a well-established technology for removal of heavy metals and hazardous anions from dilute solutions. Ion exchange can be expected to perform well for these applications when fed wastes of variable composition, provided the system's effluent is continually monitored to determine when resin bed exhaustion has occurred. As mentioned previously, however, the reliability of ion exchange is markedly affected by the presence of suspended solids. The use of sorptive resins is relatively new, and reliability under various conditions is not as well known.

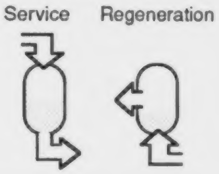
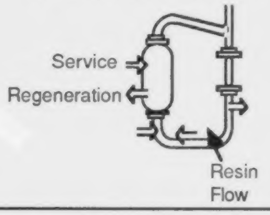
Ion exchange systems are commercially available from several vendors. The units are relatively compact and are not energy-intensive. Startup or shutdown can be accomplished easily and quickly (Ghassemi, Yu, and Quinlivan 1981). These features allow for convenient use of ion exchange and sorptive resin systems in mobile treatment systems.

Although exchange columns can be operated manually or automatically, manual operation is better suited for application at hazardous waste sites because of the diversity of wastes encountered. With manual operation, the operator can decide when to

---

* Extrapolated from data on large-sized filters in Culp, Wesner, and Culp 1978.

Figure 5-42. **Pertinent features of ion exchange systems (Chemical Separations Corporation, no date).**

Types	Countercurrent Fixed Bed 	Continuous Countercurrent 
Description of Process	Regeneration flows opposite in direction to influent. Backwash (in regeneration) does not occur on every cycle to preserve resin stage heights. Resin bed is locked in place during regeneration.	Multistage countercurrent movement of resin in closed loop, providing simultaneous treatment, regeneration, backwash, and rinse. Operation is only interrupted for momentary resin pulse.
Indications for Use	Handles high loads at moderate throughput or low loads at high throughput (gpm x TDS or gpm x ppm removal = 40,000 or more). Where effluent quality must be relatively constant, regeneration cost is critical. Disposal of single batch waste volume is no problem.	High loads with high throughputs (gpm x TDS or gpm x ppm removal = 40,000 or more). Where constant effluent quality is essential, regeneration costs are critical. Total waste volume requires small concentrated stream to be controllable. Where loss of product through dilution and waste must be minimized. Where available floor space is limited.
Advantages	Moderate capital cost. Can be operated with periodic attention. Moderate regeneration cost. Lesser volume of waste due to less frequent backwash. Consistent effluent quality.	Lowest regeneration cost. Lowest resin inventory. Consistent effluent quality. Highest throughput to floor space. Large-capacity units factory preassembled. Concentrated low-volume waste stream. Can handle strong chemical solutions and slurry. Fully automatic operation.
Disadvantages	More controls and instrumentation and higher cost. Requires mechanism to lock resin bed. Large single batches of waste disposal. Moderate water consumption through dilution and waste. Requires substantial floor space.	Requires automatic controls and instrumentation, higher capital cost. More headroom required.

stop the service cycle and begin the backwash cycle; however, this requires a skilled operator familiar with the process (Ghassemi, Yu, and Quinlivan 1981).

The use of several exchange columns at a site can provide considerable flexibility. As described previously, various resin types can be used to remove anions, cations, and organics. Also, various columns can be arranged in series to increase service life between regeneration of the lead bed or in parallel for maximum hydraulic capacity. The piping arrangement allows for one or more beds to be taken out for regeneration while the other columns remain in service (Ghassemi, Yu, and Quinlivan 1981).

Consideration must be given to the disposal of contaminated ion exchange regeneration solution. Another important operational consideration involves the selection of regeneration chemicals to ensure the compatibility of the regenerating chemical with the ground water being treated. For example, the use of nitric acid to regenerate an ion exchange column containing ammonium ions would result in the formation of ammonium nitrate, a potentially explosive compound.

5.7.7.4 Costs

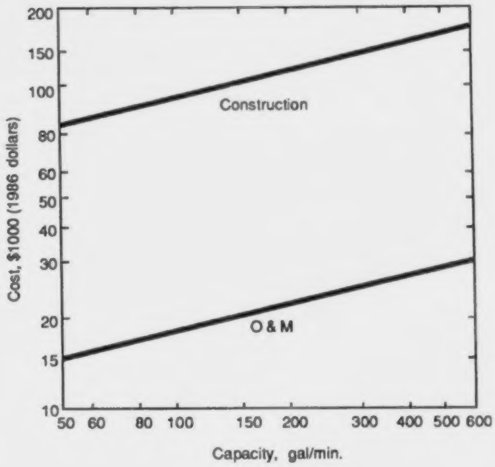
Costs of various sizes of ion exchange units are presented in Table 5-30 and Figure 5-43. The construction costs assume fabricated-steel contact vessels with baked phenolic linings, a resin depth of 6 ft, housing for the columns, and all piping and backwash facilities.

Table 5-30. **General Cost Data for Various Sizes of Ion Exchange Units[*]**

Plant Capacity (gal/min)	Construction Cost[†] ($)	O&M Costs[†] ($/yr)
50	85,600	14,800
195	118,400	21,700
305	137,300	24,700
438	156,800	28,100
597	183,500	32,100

[*] Adapted from Hansen, Gumerman, and Culp 1979.
[†] Costs were updated from 1979 to 1986 dollars by using the second-quarter Marshall and Swift Index.

Figure 5-43. **Construction and annual O&M costs for ion exchange (Hansen, Gumerman, and Culp 1979).**



Operation and maintenance costs include electricity for backwashing (after 150 bed volumes have been treated) and periodic repair and replacement costs. Costs for regenerant chemicals are not included because they will depend on the types and concentrations of target chemicals to be removed from the wastewater.

5.7.8 Oxidation/Reduction

5.7.8.1 General Description

Reduction-oxidation (redox) reactions are those in which the oxidation state of at least one reactant is raised while that of another is lowered. In chemical oxidation, the oxidation state of the treated compound(s) is raised. For example, in the conversion of cyanide to cyanate under alkaline conditions and using permanganate, the oxidation state of the cyanide ion is raised as it combines with an atom of oxygen to form cyanate. This reaction can be expressed as follows:

$$2NaCN + 2KMnO_4 + KOH \rightarrow 2K_2MnO_4 + NaCNO + H_2O$$

Common commercially available oxidants include potassium permanganate, hydrogen peroxide, chlorine gas, and calcium and sodium hypochlorite.

5.7.8.2 Application/Availability

Chemical oxidation is used primarily for detoxification of cyanide and treatment of dilute contaminated ground water containing oxidizing organics. Among the organics for which oxidative treatment has been reported are aldehydes, mercaptans, phenols, benzidine, unsaturated acids, and certain pesticides (Kiang and Metry 1982). Chemical oxidation also can be an effective way of pretreating wastes prior to biological treatment; compounds that are refractory to biological treatment can be partially oxidized, which makes them more amenable to biological oxidation.

Equipment requirements for chemical oxidation are simple and include readily available equipment such as contact vessels with agitators to provide suitable contact of the oxidant with the waste, storage vessels, and chemical metering equipment. Some instrumentation is required to determine pH and the degree of completion of the oxidation reaction. Because some oxidizing reagents react violently in the presence of significant quantities of readily oxidizable materials, reagents must be added in small quantities to avoid momentary excesses.

One of the major limitations of chemical oxidation is that the oxidation reactions frequently are incomplete (reactions do not proceed to CO_2 and H_2O). Incomplete oxidation may be due to oxidant concentration, pH, oxidation potential of the oxidant, or formation of a stable intermediate (Kiang and Metry 1982). The danger of incomplete oxidation is that more toxic oxidation products could be formed. Chemical oxidation is not well suited to high-strength, complex, waste streams. The most powerful oxidants are relatively nonselective, and any oxidizable organics in the ground water will be treated. If the ground water is highly contaminated, large concentrations of oxidizing agents will have to be added to treat target compounds. Some oxidants (e.g., permanganate) can be decomposed in the presence of high concentrations of alcohols and organic solvents (Kiang and Metry 1982).

Chemical reduction involves the addition of a reducing agent, which lowers the oxidation of a substance as a means of reducing toxicity or solubility or transforming it to a form that can be more easily handled. For example, when sulfur dioxide is used in the reduction of hexavalent chromium [Cr(VI)] to trivalent chromium [Cr(III)], the oxidation state of Cr changes from 6+ to 3+ (Cr is reduced) and the oxidization state of sulfur increases from 4+ to 6+ (sulfur is oxidized). The decrease in the positive valence or the increase in the negative valence with reduction takes place simultaneously with oxidation in chemically equivalent ratios (Kiang and Metry 1982).

$2H_2CrO_4 + 3SO_2 + 3H_2O \rightarrow Cr_2(SO_4)_3 + 5H_2O$

Commonly used reducing agents include sulfite salts (e.g., sodium bisulfite, sodium metabisulfite, sodium hydrosulfite), sulfur dioxide, and the base metals (iron, aluminum, and zinc).

Chemical reduction is well demonstrated for the treatment of lead, mercury, and chromium. For complex waste streams containing other potentially reducible compounds, however, laboratory- and pilot-scale tests will be required to determine appropriate chemical feed rates and reactor retention times.

Chemical reduction can be carried out using simple, readily available equipment and reagents. Capital and operating costs are low and the process is easy to implement.

5.7.8.3 Design and Construction Considerations

Implementation is complicated because every oxidation/reduction reaction system must be designed for the specific application. Laboratory- and/or pilot-scale testing is essential to determine the appropriate chemical feed rates and reactor retention times in accordance with reaction kinetics. Oxidation/reduction has not been widely used to treat ground water.

A major consideration in electing to use oxidation is that the treatment chemicals are invariably hazardous and require great care in handling. In particular, many oxidizing agents are potentially hazardous to handle and suppliers' instructions should be carefully followed.

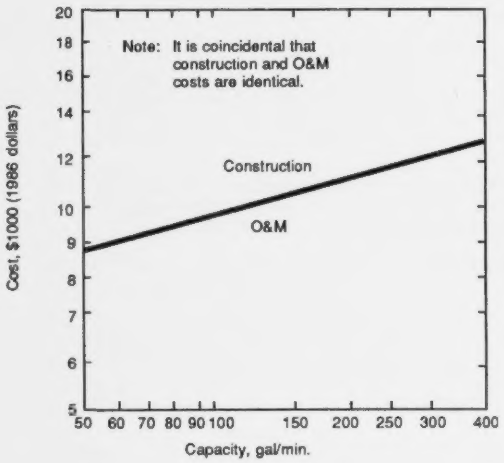
Oxidation can produce some undesirable byproducts. For example, the addition of chlorine can result in the formation of bioresistant end products that can be odorous and more toxic than the original compound. The possibility of this undesirable side reaction needs to be considered when chlorine is used for oxidation of contaminated ground water (Conway and Ross 1980).

The required equipment for chemical reduction is very simple. It includes storage vessels for the reducing agents and perhaps for the contaminated ground water, metering equipment for both streams, and contact vessels with agitators to provide suitable contact of reducing agent and ground water. Some instrumentation is also required to determine the concentration and pH of the ground water and the degree of completion of the reduction reaction. The reduction process may be monitored by an oxidation-reduction potential (ORP) electrode (Kiang and Metry 1982).

5.7.8.4 Costs

Capital costs for both chemical oxidation and chemical reduction include costs for chemical storage, chemical feeding, and chemical mixing. Approximate costs are shown in Figure 5-44.

Figure 5-44. Construction and annual O&M costs for chemical oxidation and reduction.



5.7.9 *Neutralization*

5.7.9.1 General Description

Neutralization consists of adding acid or base to contaminated ground water to adjust its pH. The most common system for neutralizing acidic or basic ground-water streams involves a multiple compartmental basin, usually constructed of reinforced plastic or lined concrete.

To reduce the volume of the neutralization basin to the required level, mixers are installed in each compartment to provide more intimate contact between the contaminated ground water and neutralizing reagents. This speeds up reaction time. Stainless steel plates mounted on the floor of the pit and directly below the mixers reduce corrosion damage to the structure. Basin inlets are baffled to provide flow distribution; effluent baffles can help to prevent foam from being carried over into the receiving stream (Conway and Ross 1980).

5.7.9.2 Application/Availability

Neutralization can be applied to any ground-water stream requiring pH control. It commonly precedes biological treatment because bacteria are sensitive to rapid pH changes and values outside a pH range of 6 to 9. Aquatic ecosystems are similarly pH-sensitive; therefore, ground water must be neutralized prior to discharge to a receiving water body. When contaminated ground water is hazardous because of its corrosivity, neutralization may be required before its acceptance for disposal. It is also used as a pretreatment for several chemical treatment technologies, including carbon adsorption, ion exchange, air stripping, wet-air oxidation, and chemical oxidation/reduction processes. A pH adjustment is also dictated in several other situations; e.g., for protection of construction materials, breaking of emulsions, insolubilization of certain organic materials, and control of chemical reaction rates (Conway and Ross 1980).

Neutralization is a relatively simple treatment process that can be performed with readily available equipment. Only storage and reaction tanks with accessory agitators and delivery systems are required. Because of the corrosivity of the wastes and treatment reagents, appropriate materials of construction are needed to provide a reasonable service life for equipment. The process is reliable provided pH monitoring units are used. The feed of the neutralization agent may be regulated automatically by the pH monitoring unit, which ensures effective neutralization and minimizes worker contact with corrosive neutralizing agents.

5.7.9.3 Design and Construction Considerations

The amount of neutralizing reagent is readily computed from the stoichiometry of the acid-base reaction and the concentration of the reagent and the waste stream. The choice of an acidic reagent for neutralization of an alkaline ground water is generally between sulfuric acid and hydrochloric acid. Sulfuric acid is normally selected because of its lower cost. Hydrochloric acid generally forms soluble reaction end products that may be advantageous.

The choice of a caustic reagent is generally between sodium hydroxide and various limes; magnesium hydroxide and ammonium hydroxide are also used. The factors to be considered in choosing the most suitable reagent include purchase cost, neutralization capacity, reaction rate, storage and feeding requirements, and neutralization products. Although sodium hydroxide costs much more than the other materials, it is frequently used because of its uniformity, ease of storage and feeding, rapid reaction rate, and soluble end products. The lime materials have the advantage of relatively low cost; this low cost is at least partially offset by increased capital and operating costs for the more complex feeding and reaction system that is required (Conway and Ross 1980).

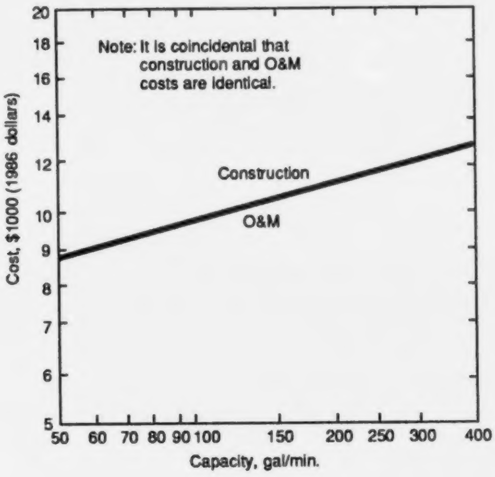
Although the rate of reaction between the completely ionized sodium hydroxide and a strong acid-contaminated ground water is virtually instantaneous, the reactions of lime bases require considerable time for completion. Reaction time can be minimized by several approaches: a relatively high end-point pH level (approximately 9), efficient mixing, and slurry feeding as opposed to dry feeding (Conway and Ross 1980).

Neutralization of ground water can produce air emissions. Acidification of streams containing certain salts (e.g., sulfide) will produce toxic gases. Feed tanks should be totally enclosed to prevent the escape of fumes. Adequate mixing should be provided to disperse the heat of reaction if concentrated wastes are being treated. The process should be controlled from a remote location if possible. A sturdy, shielded electrode that can be routinely cleaned or replaced should be mounted near the discharge point and connected to a pH meter.

5.7.9.4 Costs

Capital costs for a neutralization system include costs for chemical storage, chemical feeding, and mixing. Reagent cost is the primary operating cost. Approximate costs are shown in Figure 5-45.

Figure 5-45. Construction and annual O&M costs for neutralization.



5.7.10 *Steam Stripping*

5.7.10.1 General Description

Steam stripping is used to remove gases or volatile organics from dilute contaminated ground-water streams. This process is essentially a fractional distillation of volatile compounds from a ground-water stream. The volatile component may be a gas or volatile organic compound with solubility in the wastewater stream. In most instances, the volatile component (e.g., methanol or ammonia) is quite water soluble.

Steam stripping is usually conducted as a continuous operation in a packed tower or conventional fractionating distillation column (bubble cap or sieve tray) with more than one stage of vapor/liquid contact. The preheated contaminated ground water from the heat exchanger enters near the top of the distillation column and then flows by gravity countercurrently to the steam and organic vapors (or gas) rising up from the bottom of the column. As the contaminated ground water passes down through the column, it contacts the vapors rising from the bottom, which contain progressively less volatile organic compound or gas, until it reaches the bottom of the column, where the ground water is finally heated by the incoming steam to reduce the concentration of volatile component(s) to their final concentration. Much of the heat in the water discharged from the bottom of the column is recovered during preheating of the feed to the column.

Reflux (condensing a portion of the vapors from the top of the column and returning it to the column) may or may not be practiced, depending on the desired composition of the vapor stream. Although many of the steam strippers in industrial use introduce the wastewater at the top of the stripper, introducing the feed to a tray below the top tray has its advantages when reflux is used. Introducing the feed at a lower tray (while still using the same number of trays in the stripper) will either reduce steam requirements (because less reflux is needed) or will yield a vapor stream richer in volatile component. Combining reflux with the introduction of the feed at a lower tray will increase the concentration of the volatile organic component beyond that obtainable by reflux alone. Figure 5-46 is a flow diagram of a steam stripping system.

5.7.10.2 Application/Availability

Steam stripping has been used for many years for the recovery of ammonia from coke oven gas. With the recent advent of more stringent water effluent regulations, contaminated ground-water streams are being treated by steam stripping for removal of volatile organic components (i.e., methanol from pulp mill condensate).

Three common examples of product recovery by steam stripping are ammonia recovery (for sale as ammonia or ammonia sulfate) from coke oven gas scrubber water, sulfur from refinery sour water, and phenol from water solution in the production of phenol. This technology has been recently applied to ground-water treatment; even newer applications include removal of phenols, mercaptans, and chlorinated hydrocarbons from wastewater.

Equipment is nearly the same as that required for conventional fractional distillation (i.e., packed column or tray tower, reboiler, reflux condenser and feed tanks, and pumps); however, the heat exchanger is used for heating feed entering the column and cooling the stripped contaminated ground water leaving the column. The reboiler is often an integral part of the tower body rather than a separate vessel.

5.7.10.3 Design and Construction Considerations

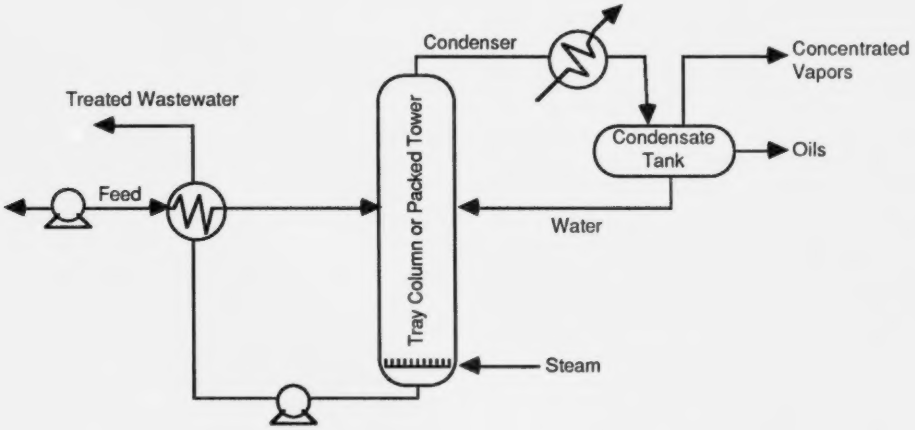
Typical design criteria are shown below.

Column height, 20 to 60 ft
Column diameter, 3 to 6 ft
Steam requirements, 0.6 to 2.9 lb/gal
Typical wastewater flow, 200 gal/min

The selection of materials of construction depends on the operating pH and presence (or absence) of corrosive ions (sulfides, chlorides).

Steam-stripped volatiles are usually processed further for recovery or incinerated. If stripped volatiles contain sulfur and are incinerated, the impact of SO_2 emissions must be considered. The impact of the stripped ground water depends on the quantity and type of residual volatile organics remaining in the stripped

Figure 5-46. Steam stripping system.

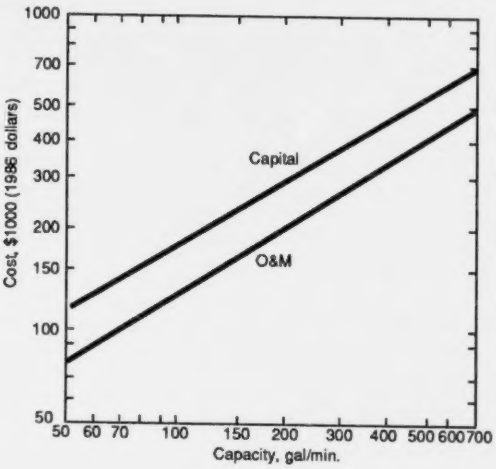


ground water. Land requirements are small, and the only discharge generally is the treated ground water. Use of steam stripping requires a source of steam. Steam stripping is thus not suitable for emergency field use unless the contaminated ground water can be transported from the site to a steam stripping facility (EPA 1980).

5.7.10.4 Costs

The total capital costs and annual operating costs are shown in Figure 5-47 (in mid-1986 dollars).

Figure 5-47. Capital and annual O&M costs for steam stripping.



5.7.11 *Reverse Osmosis*

5.7.11.1 General Description

In reverse osmosis (RO), high pressure is used to force a solvent (e.g., water) through a membrane that is permeable to the solvent molecules but not to the solute molecules. In industrial applications, it is used primarily to demineralize brackish waters and to treat a variety of industrial wastewaters.

The basic components of an RO unit are the membrane, a membrane support structure, a containing vessel, and a high-pressure pump. The membrane and membrane support structure are the most critical elements.

5.7.11.2 Application/Availability

Reverse osmosis is used to reduce the concentrations of dissolved solids, both organic and inorganic. In the treatment of contaminated ground water, use of RO would be limited primarily to polishing low-flow streams containing highly toxic contaminants. In general, good removal can be expected for high-molecular-weight organics and charged anions and cations. Multivalent ions are treated more effectively than are univalent ions. Recent advances in membrane technology have made it possible to remove such low-molecular-weight organics as alcohols, ketones, amines, and aldehydes (Gooding 1985). Table 5-31 shows removal results obtained during testing of a mobile RO unit using two favorable membrane materials (Whittaker 1984).

Reverse osmosis units are subject to chemical attack, fouling, and plugging. Pretreatment requirements

Table 5-31. Results of Pilot Scale Testing of a Reverse Osmosis Unit[*]

Chemical	Feed Concentration (ppb)	Concentration in Concentrate (ppb)	Percent Removed in Permeate: Polyether-polysulphone Membrane	Percent Removed in Permeate: Polyester/Amide Polysulphone Membrane
Dichloromethane	406	203	58	52
Acetone	110	355	84	76
1,1-Dichloroethene	34	795	99	95
Tetrahydrofuran	17,890	467	98	89
Diethyl ether	210	439	97	89
Chloroform	270[†]	567	98	92
1,2-Dichloroethane	99	415	92	85
1,1,1-Trichloroethane	659	651	99.8	97
Trichloroethene	24	346	99	92
Benzene	539	491	99	99
Bromoform	12[†]	633	99.1	98
Hexane	10[†]	704	99.8	97

[*] Data from Whittaker 1984.
[†] No standard available; concentration estimated.

can be extensive. Contaminated ground water must be pretreated to remove oxidizing materials such as iron and manganese salts; to filter out particulates; to adjust pH to a range of 4.0 to 7.5; and to remove oil, grease, and other film forms (De Renzo 1978). The growth of slimy biomass on the membrane surface or the presence of organic macromolecules may also foul the membrane. This organic fouling can be minimized by perchlorination, the addition of biocides, and/or pretreatment with activated carbon (Ghassemi, Yu, and Quinlivan 1981).

Compact RO units are commercially available, can be started easily and shut down relatively quickly, can be serviced conveniently, produce only a small volume of residue (10 to 25 percent of the feed), do not require skilled labor, and can be operated with electric power produced on site. Thus, RO meets many of the requirements of a mobile system; however, a significant amount of time may be required to obtain and assemble the necessary components. Another major shortcoming is membrane susceptibility to fouling or degradation caused by the presence of suspended solids or strong oxidizers in the contaminated ground water or ground water with a very low pH. For this reason, pretreatment of the ground water (e.g., by coagulation/flocculation) is necessary before treatment by RO. Depending on the specific contaminants to be removed and the type of membrane used, RO is generally used as a final polishing step. Another consideration is that a certain amount of concentrated waste material will require further treatment or disposal. Also, if the system is to be located on a remote site, power consumption can be a problem. A 10-gal/min system will require about 5 kW of power. This is generally not a problem at service station sites, however.

Finally, RO will not reliably treat wastes with a high organic content because the membrane may dissolve in the waste. Lower levels of organic compounds may also be detrimental to the unit's reliability because biological growth may form on a membrane fed an influent containing biodegradable organics.

5.7.11.3 Design and Construction Considerations

The most critical design consideration applicable to RO technology is the design of the semipermeable membrane. In addition to achieving the required degree of separation at an economic flux level under ideal conditions, the design of the membrane must be such that it can be incorporated in an operating system that satisfies the following practical requirements (Conway and Ross 1980):

- Minimum concentration polarization, i.e., ratio of impurity concentration at the membrane surface to that in the bulk stream.
- High packing density, i.e., membrane surface area per unit volume of the pressure module.
- Ability to handle any particulate impurities (by proliferation if necessary).
- Adequate support for the membrane and other physical features such as effectiveness of seals, ease of membrane replacement, and ease of cleaning.

Membranes are usually fabricated in flat sheets or tabular forms and then assembled into modules. The most common materials of construction are cellulose acetate and other polymers, such as polyamides and polyether-polysulphone. There are three basic module designs: tubular, hollow fiber, and spiral-wound (Figure 5-48). Each has its own advantages and limitations. The tubular module provides the largest flow channel and allows for turbulent fluid flow; thus, it is least susceptible to plugging caused by suspended solids and has the highest flux. Because of its small area/volume ratio, however, the total product recovered per module is small. The cost of a tubular module is approximately five times greater than that for the other modules for an equivalent rate of water recovery, and the total space requirement is about three to five times greater than that for the spiral-wound system (Ghassemi, Yu, and Quinlivan 1981).

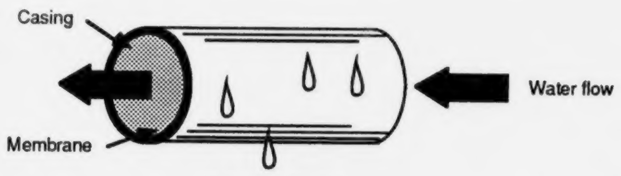
A hollow-fiber membrane is constructed of polyamide polymers (duPont) and cellulose triacetate (Dow). The polyamide membrane permits a wider operating pH range than does cellulose acetate, which is commonly used for the construction of spiral-wound and tubular membranes. The flow channel and the flux are about an order of magnitude lower than on the other configurations. This small flux, however, is compensated for by the large surface area/volume ratio; therefore, the total product water per module is close to that obtainable with spiral-wound modules. Because of the small size of the channels (about 0.004 in.) and the laminar fluid flow within the channels, however, this module is susceptible to plugging, and extensive pretreatment may be required to protect the membrane (Ghassemi, Yu, and Quinlivan 1981).

The spiral-wound module consists of an envelope of flat-sheet membranes rolled around a permeate collector tube. This configuration provides for a higher flux and greater resistance to fouling than does the configuration of the hollow-fiber modules; it is also less expensive and occupies less space than a tubular module (Ghassemi, Yu, and Quinlivan 1981).

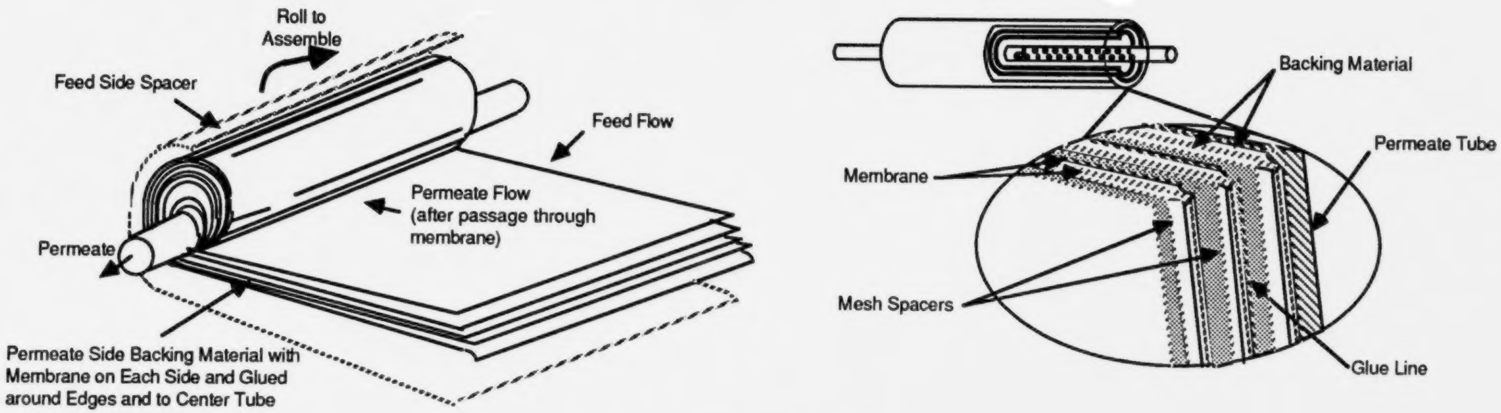
5.7.11.4 Costs

Figure 5-49 presents the costs of various sizes of RO units. Construction costs include housing, tanks, piping, membranes, flow meters, cartridge filters, acid and polyphosphate feed equipment, and cleanup equipment. These costs are based on influent total dissolved solids concentrations of less than 10,000 ppm.

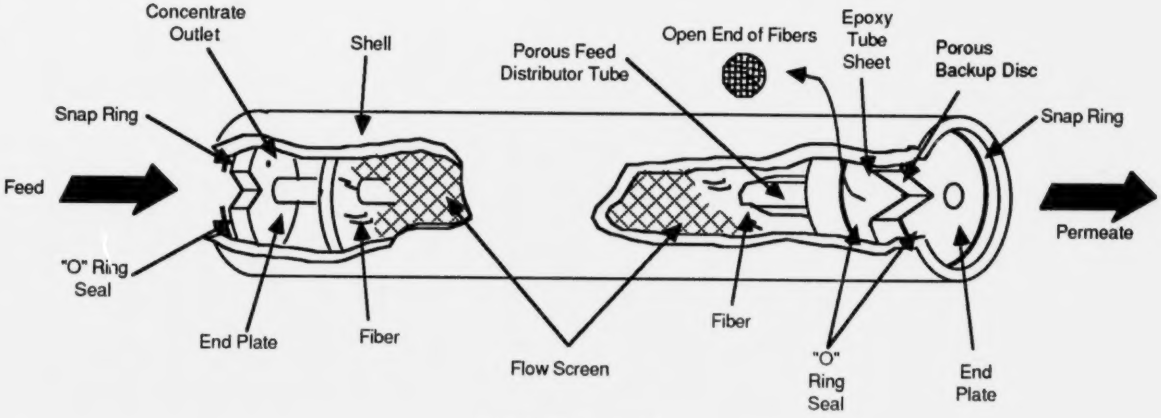
Figure 5-48. Reverse osmosis membrane module configurations (Ghassemi, Yu, and Quinlivan 1981).


Casing
Membrane
Water flow

Tubular Model

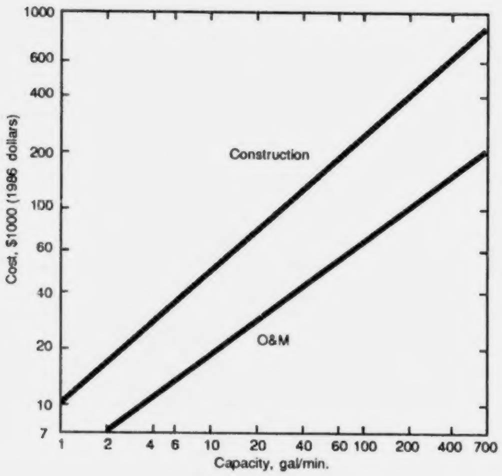

Roll to Assemble
Feed Side Spacer
Feed Flow
Permeate Flow (after passage through membrane)
Permeate
Permeate Side Backing Material with Membrane on Each Side and Glued around Edges and to Center Tube
Backing Material
Permeate Tube
Membrane
Mesh Spacers
Glue Line

Spiral-wound module


Concentrate Outlet
Shell
Porous Feed Distributor Tube
Open End of Fibers
Epoxy Tube Sheet
Porous Backup Disc
Snap Ring
Feed
"O" Ring Seal
End Plate
Fiber
Flow Screen
Fiber
"O" Ring Seal
End Plate
Snap Ring
Permeate

Hollow-fiber model

Figure 5-49. **Concentration and annual O&M costs for reverse osmosis.**



The operation and maintenance costs include electricity for the high-pressure feed pumps (450 psi operating pressure), building utilities, routine periodic repair, routine cleaning, and membrane replacement every 3 years. Operation and maintenance costs do not include costs for pretreatment chemicals because usage rates vary greatly among plants.

5.7.12 Sludge Dewatering

5.7.12.1 General Description

Sludge dewatering can be achieved by several different types of filtration mechanisms. The four major dewatering methods are described briefly in the following subsections:

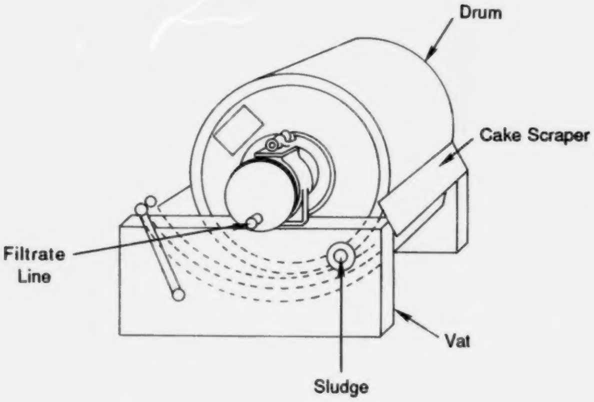
Vacuum Filtration

A rotary vacuum filter consists of a cylindrical drum rotating partially submerged in a vat or pan of conditioned sludge. The drum is divided radially into several sections that are connected through internal piping to ports in a valve body (plate) at the hub. This plate rotates in contact with a fixed valve plate with similar parts that are connected to the appropriate service. Various operating zones are encountered during a complete revolution of the drum. In the pickup or form section, vacuum is applied to draw liquid through the filter covering (media), which forms a cake of partially dewatered sludge. As the drum rotates, the cake emerges from the liquid sludge pool while suction is maintained to promote further dewatering. A lower level of vacuum often exists in the cake-drying zone. If the cake tends to adhere to the media, a scraper blade may be provided to assist in its removal.

The three principal types of rotary vacuum filters are the drum type, coil type, and belt type. The filters differ primarily in the type of covering used and the cake discharge mechanism employed. A cloth medium is used on drum and belt types; stainless steel springs are used on the coil type. Occasionally, a metal medium is used on belt types. The drum filter also differs from the other two in that the cloth covering does not leave the drum, but is washed in place when necessary. The design of the drum filter provides considerable latitude in the amount of cycle time devoted to cake formation, washing, and dewatering; the design also minimizes inactive time.

A schematic diagram of a drum-type rotary vacuum filter is shown in Figure 5-50.

Figure 5-50. **Drum-type rotary vacuum filter.**



Filter Press Dewatering

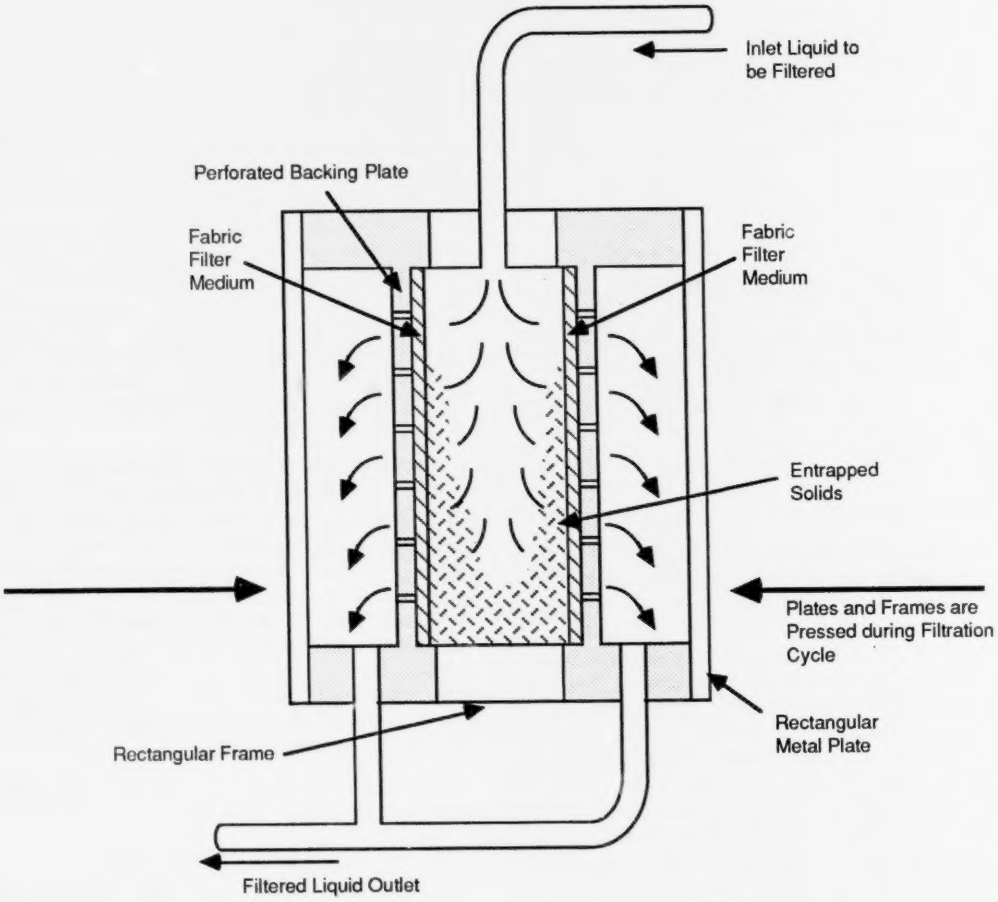
The recessed plate press, which is the conventional filter press used for dewatering sewage sludges, consists of vertical recessed plates up to 5 ft in diameter (or 5 ft on a side, if square) that are held rigidly in a frame and pressed together between a fixed and moving end. A filter cloth is mounted on the face of each plate. The sludge is fed into the press at pressures up to 225 psig and passes through feed holes in the trays along the length of the press. The water passes through the cloth; the solids are retained and form a cake on the surface of the cloth. Sludge feeding is stopped when the cavities or chambers between the plates are completely filled. Drainage ports are provided at the bottom of each press chamber. The filtrate is collected in these ports, taken to the end of the press, and discharged to a common drain. At the beginning of a processing cycle, the drainage from a large press can be on the order of

2000 to 3000 gal/h. This rate falls rapidly to about 500 gal/h as the cake begins to form; when the cake completely fills the chamber, the rate is virtually zero. The dewatering step is complete when the filtrate is near zero. At this point, the pump feeding sludge to the press is stopped, and any back pressure in the piping is released through a bypass valve. The electrical closing gear is then operated to open the press. The individual plates are moved, in turn, over the gap between the plates and the moving end; this allows the filter cakes to fall out. The plate-moving step can be either manual or automatic. When all of the plates have been moved and the cakes released, the complete pack of plates is pushed back by the moving end and closed by the electrical closing gear. The valve to the press is then opened, the sludge feed pump is started, and the next dewatering cycle commences. Thus, a cycle includes the time required for filling, pressing, cake removal, media washing, and press closing. Figure 5-51 is a schematic diagram of a filter press plate.

Belt Filter Dewatering

A belt filter consists of an endless filter belt that runs over a drive and guide roller at each end, much as a conveyor belt does. The upper side of the filter belt is supported by several rollers. A press belt above the filter belt runs in the same direction and at the same speed; its drive roller is coupled with the drive roller of the filter belt by means of a pressure-roller system whose individual rollers can be adjusted horizontally and vertically. The sludge to be dewatered is fed on the upper face of the filter belt and is continuously dewatered between the filter and press belts. After the sludge passes through the pressure zone, further dewatering in a reasonable time cannot be achieved

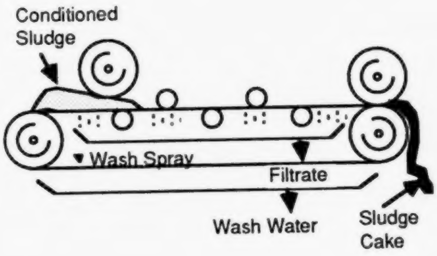
Figure 5-51. Filter press plate (DeRenzo 1978).


Inlet Liquid to be Filtered
Perforated Backing Plate
Fabric Filter Medium
Fabric Filter Medium
Entrapped Solids
Plates and Frames are Pressed during Filtration Cycle
Rectangular Frame
Rectangular Metal Plate
Filtered Liquid Outlet

by the application of static pressures alone; however, a superimposition of shear forces can effect this further dewatering. The supporting rollers of the filter belt and the pressure rollers of the pressure belt are adjusted in such a way that the belts and the sludge between them form an S-shaped curve. This causes a parallel displacement of the belts relative to each other due to the differences in the radii. After further dewatering in the shear zone, the sludge is removed by a scraper.

Some units operate in two stages; the initial draining zone is on the top level, and pressing and shearing take place in an additional lower section. A significant feature of the belt filter press is its use of a coarse-mesh, relatively open-weave, metal-medium fabric. The use of such fabric is possible because of the rapid and complete cake formation obtainable when proper flocculation is achieved. Belt filters do not need vacuum systems, and they do not have the sludge pickup problem occasionally encountered with rotary vacuum filters. The belt filter press system includes auxiliaries such as equipment for preparing polymer solution and automatic process controls. A schematic diagram of a belt filter press system is shown in Figure 5-52.

Figure 5-52. Belt filter press.



Centrifugal Dewatering

The solid-bowl continuous centrifuge assembly consists of a bowl and conveyor joined through a planetary gear system designed to rotate the bowl and the conveyor at slightly different speeds. The solid cylindrical bowl, or shell, is supported between two sets of bearings. A conical section at one end of the bowl forms the dewatering beach over which the helical conveyor screw pushes the sludge solids to outlet ports and then to a sludge cake discharge hopper. The opposite end of the bowl is fitted with an adjustable outlet weir plate for regulating the level of the sludge pool in the bowl. The centrate flows through outlet ports either by gravity or by a centrate pump attached to the shaft at one end of the bowl. Sludge slurry enters the unit through a stationary feed pipe that extends into the hollow shaft of the rotating bowl and passes to a baffled, abrasion-protected chamber for acceleration before it is discharged through the feed ports in the rotating conveyor hub into the sludge pool. The centrifugal forces cause the sludge pool to take the form of a concentric annular ring on the inside of the bowl. Solids settle through this ring to the wall of the bowl, where they are picked up by the conveyor scroll. Separate motor sheaves or a variable-speed drive can be used to adjust the bowl speed for optimum performance.

Bowls and conveyors can be constructed from a large variety of metals and alloys to suit special applications. For dewatering of ground-water sludges, mild steel or stainless steel is normally used. Because of the abrasive nature of many sludges, hardfacing materials are applied to the leading edges and tips of the conveyor blades, the discharge ports, and other wearing surfaces. New wearing surfaces may be welded on when required.

In the continuous concurrent solid-bowl centrifuge, incoming sludge is carried by the feed pipe to the end of the bowl opposite the discharge. Centrate is skimmed off and the cake proceeds up the beach for removal. As a result, settled solids are not disturbed by incoming feed.

In the disc-type centrifuge, the incoming stream is distributed between a multitude of narrow channels formed by stacked conical discs. Suspended particles have only a short distance to settle, so that small and low-density particles are readily collected and discharged continuously through fairly small orifices in the bowl wall. The clarification capability and throughput rate are high, but sludge concentration is limited by the necessity of discharging through orifices 0.050 to 0.100 in. in diameter. Therefore, the disc-type centrifuge is generally considered a thickener rather than a dewatering device.

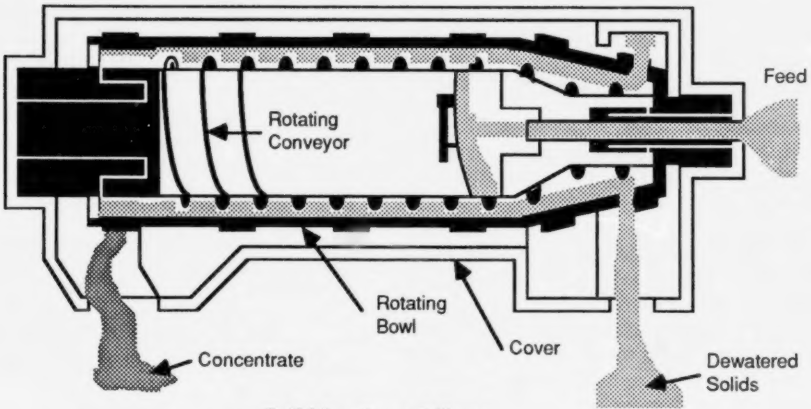
In the basket-type centrifuge, flow enters the machine at the bottom and is directed toward the outer wall of the basket. Cake continually builds up within the basket until the centrate, which overflows a weir at the top of the unit, begins to increase in solids. At that point, feed to the unit is shut off, the machine decelerates, and a skimmer enters the bowl to remove the liquid layer remaining in the unit. A knife is then moved into the bowl to cut out the cake, which falls out of the open bottom of the machine. This is a batch-drive unit with alternate charging of feed sludge and discharging of dewatered cake.

Schematic diagrams of the various types of centrifuges are shown in Figure 5-53.

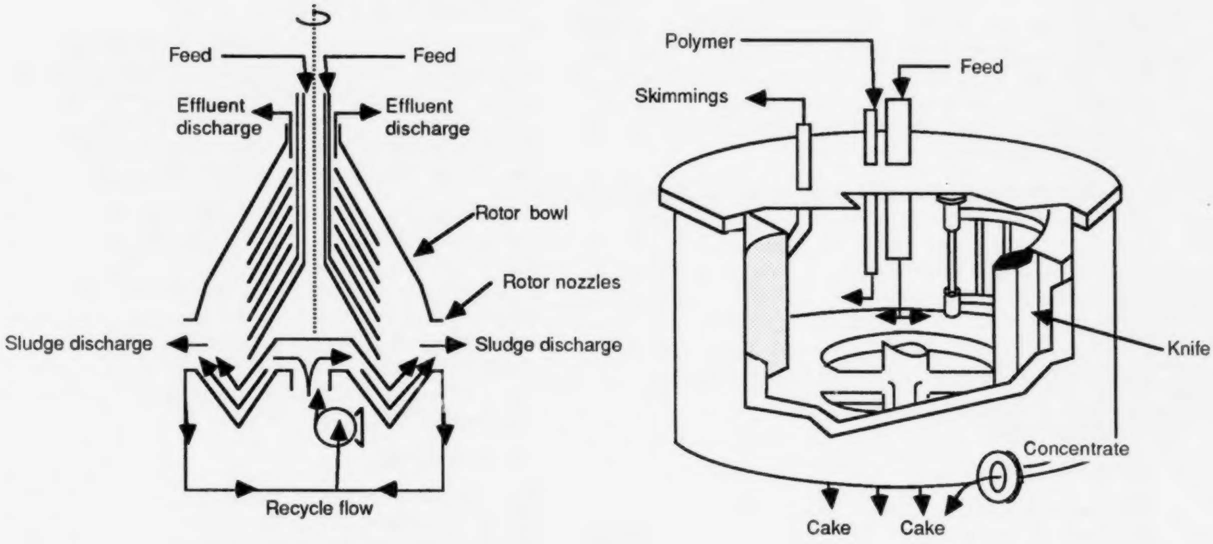
5.7.12.2 Application/Availability

Vacuum filtration is the most common method of mechanical sludge dewatering in the United States. Vacuum filtration units are available in various sizes,

Figure 5-53. Types of centrifuges (EPA 1979).


Feed
Rotating
Conveyor
Rotating
Bowl
Cover
Concentrate
Dewatered
Solids

Solid-bowl centrifuge


Feed
Feed
Effluent
discharge
Effluent
discharge
Rotor bowl
Rotor nozzles
Sludge discharge
Sludge discharge
Recycle flow
Polymer
Feed
Skimmings
Knife
Concentrate
Cake
Cake

Disc-type centrifuge

Basket-type centrifuge

and they are generally used in larger facilities where space is limited or when incineration is necessary for maximum volume reduction. The operation is sensitive to the type of sludge and conditioning procedures. Solids capture ranges from 85 to 99.5 percent and cake moisture is usually 60 to 90 percent, depending on feed type, solids concentration, chemical conditioning, machine operation, and management. Dewatered cake is suitable for landfilling, heat drying, incineration, or land spreading.

Filter-press dewatering is used for hard-to-handle sludges and when filtration must be accomplished in a small area. Batch discharge requires equalization of pressed cake prior to incineration if adopted. For input sludges of varying types with a total suspended solids (TSS) content of 1 to 10 percent, typical filter press production data show cake solids concentrations of 50 percent with fly-ash conditioning (100 to 250 percent on dry solids basis) and cycle times of 1.5 to 2.0 h. Cake solids concentrations of 45 percent have been achieved with chemical conditioning (5 to 7.5 percent $FeCl_3$ and 10 to 15 percent lime) and cycle times of 1.0 to 2.0 h. In general, cakes of 25 to 50 percent solids concentrations are achieved.

Belt filter press use in the United States is on the increase. Its major advantages are that it is the least energy-intensive filtration-method and it can be used to treat sludges that are difficult to dewater. This process can be used where a filtration must be accomplished in a small area. Its disadvantage is that it is sensitive to incoming feed characteristics and requires sludge conditioning.

Centrifugal dewatering with solid-bowl and disc-type centrifuges is in widespread use. Solid-bowl and disc-type centrifuges are generally used for dewatering sludge in larger facilities where space is limited or where sludge incineration is required. Basket-type units are used primarily for partial dewatering at small plants. Disc-type centrifuges are more useful for thickening and clarification than for dewatering.

5.7.12.3 Design and Construction Considerations

Vacuum Filtration

The design load is a function of feed solids concentrations, subsequent processing requirements, and chemical preconditioning. Typical loads for vacuum filtration are shown below.

Sludge Type	Typical Loading (lb dry solids/ft^2 per hour)
Raw primary	7 to 15
Digested primary	4 to 7
Mixed digested	3.5 to 5

Filter Press Dewatering

Typical design criteria for filter presses are as follows:

Chamber volume	0.75 to 2.8 ft^3/chamber
Filter areas	14.5 to 45 ft^2/chamber
Number of chambers	Up to 100
Sludge cake thickness	1 to 1.5 in.
Sludge feed rate	Approximately 2 lb/cycle per ft^2 (dry solids basis)

The presses must normally be installed well above floor level so that the filter cake can drop onto conveyors or trailers.

Belt Filter Dewatering

Typical design criteria for loadings, based on active belt area, are as follows:

Sludge Type	Sludge Loading (gal/ft^2 per hour)	Dry Solids Loading (lb/ft^2 per hour)
Raw primary	27 to 34	13.5 to 17
Digested primary	20 to 24	20.5 to 24
Digested mixed/ secondary	13 to 17	6.7 to 8.4

Centrifugal Dewatering

Each installation is site-specific and depends on the manufacturer's product line. Maximum capacities of about 100 tons/h of dry solids are available in solid-bowl units with diameters up to 54 in. and power requirements up to 175 hp. Disc-type units are available with capacities up to 400 gal/min of concentrate.

Centrifugation requires a sturdy foundation because the operation generates vibration and noise. Adequate electric power also must be provided for the large motors required. The major difficulty encountered in the operation of centrifuges has been the disposal of the centrate, which is relatively high in suspended nonsettling solids. With disc-type units, the feed must be degritted and screened to prevent pluggage of discharge orifices.

5.7.12.4 Costs

Figures 5-54 and 5-55 present the total capital and annual operating costs (in 1986 dollars) for vacuum filters and filter presses and for belt presses and centrifuges, respectively.

Figure 5-54. Capital and annual O&M costs for vacuum filters and filter presses (EPA 1982).

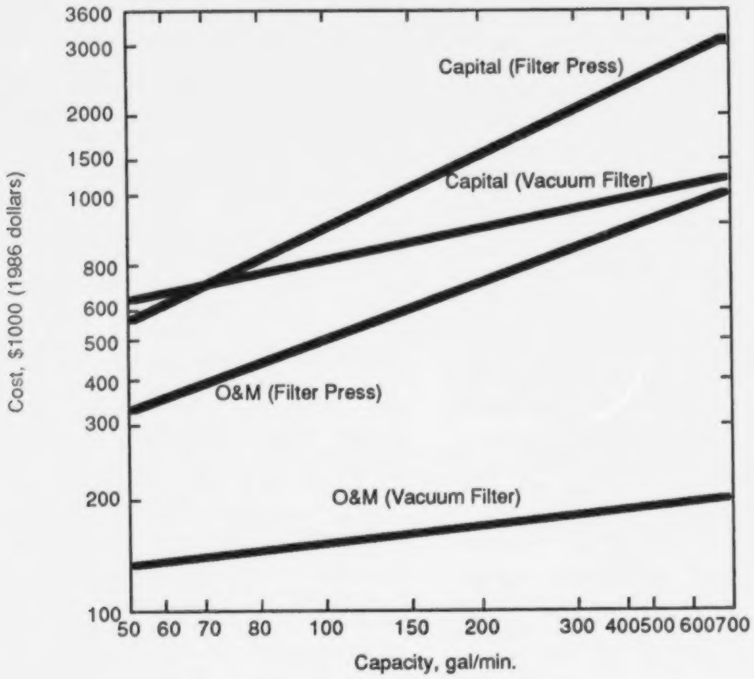
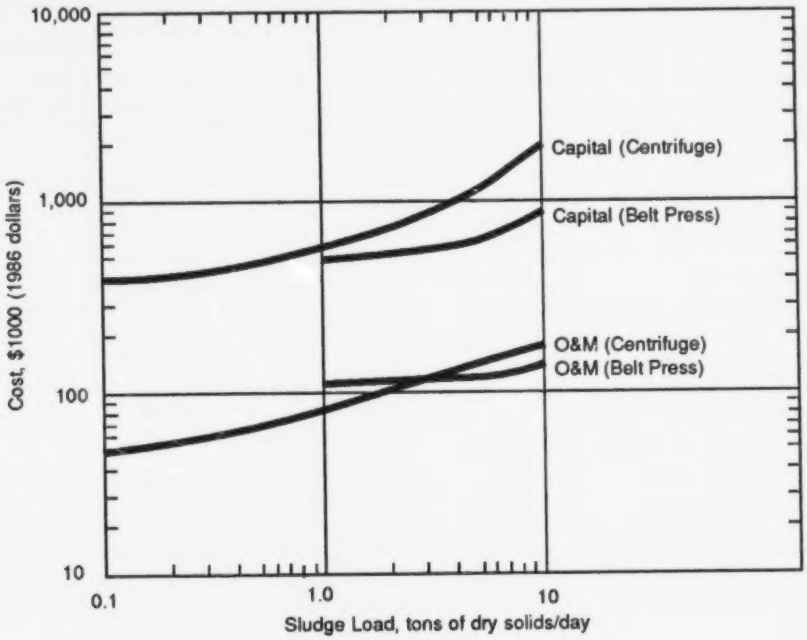


Figure 5-55. Capital and annual O&M costs for belt presses and centrifuges (EPA 1982).



5.8 Vapor Migration Control, Collection, and Treatment

Leaks from underground storage systems can present problems due to vapors emanating from the plume. Many things contribute to the path these vapors take. Normally, they vent vertically through the cover material; however, if this vertical path is sealed by frost, rain-saturated cover soil, or pavement, they tend toward lateral migration. A sand/gravel environment generally promotes greater lateral movement of vapors than does a clay environment. Because vapor migration and venting can create significant hazards, special control systems have been developed to alleviate these problems. This section presents information on the following technologies for collecting, controlling, and disposing of vapors from underground spills: passive collection systems, active collection systems, ventilation of structures, adsorption, and flaring.

5.8.1 Passive Collection Systems (EPA 1985a)

5.8.1.1 General Description

Subsurface migration of vapors beyond the leak site can be prevented by the use of passive vapor-control systems, i.e., systems that control vapor movement by altering the paths of flow without the use of mechanical components. Passive systems may be further categorized as high-permeability or low-permeability systems.

High-permeability systems entail the installation of highly permeable (relative to the surrounding soil) trenches or wells between the plume and the area to be protected. High-permeability systems generally take the form of trenches or wells excavated outside of the plume limit and backfilled with a highly permeable medium, such as a coarse crushed stone (Figure 5-56).

Low-permeability systems effectively block vapor flow into areas of concern by the use of barriers between the plume and the area to be protected (Figure 5-57).

These two concepts (high- and low-permeability) of passive vapor control are often combined in the same system to provide controlled venting of vapors and blockage of available paths for vapor migration.

5.8.1.2 Application/Availability

Passive vapor-control systems can be used at virtually any site where an excavation can be trenched or drilled to at least the same depth as the plume. Limiting factors include the presence of a perched water table or rock strata. Passive vents are generally less effective in areas of high rainfall or prolonged freezing temperatures.

5.8.1.3 Design and Construction Considerations

Passive collection is usually controlled through the use of trenches constructed around the plume. Minimum trench widths of 3 feet are often specified to ensure an open trench over the full depth. The depth of the trench is dictated by local site conditions and in some applications the trench need not be very deep just as long as it is deep enough to intercept all possible avenues of vapor migration.

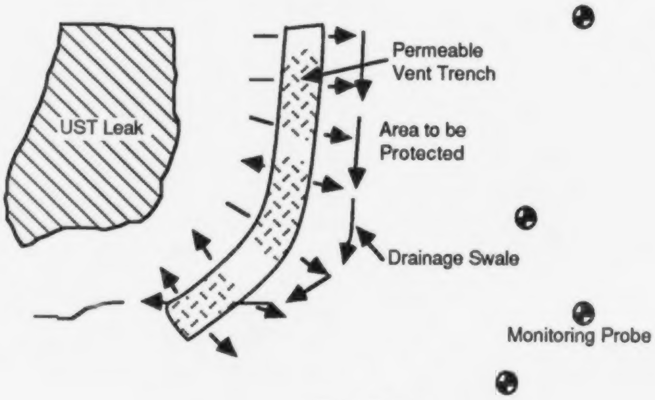
Crushed stone or river gravel is normally used as the permeable medium for trench backfill. Stone sizes greater than 1/4-inch are recommended; fine material should not be used. Horizontal perforated pipe and vertical solid wall-riser pipes are often used to ensure that paths of vapor flow to the atmosphere remain open in the event that the top of the trench becomes blocked by ice, snow, vegetation, etc. The ground surface should be graded to drain away from the trench to prevent soil from washing into the voids of the stone. Any drainage swales that must cross the trench should be installed by using enclosed conduits or paved channels.

Trenches for low-permeability systems would normally be situated and excavated in a manner similar to that used to install a high-permeability system. Width and depth requirements would be essentially the same. In lieu of the highly permeable stone backfill, however, low-permeability material would be placed in the trench. Synthetic membranes are normally used as barriers in this application.

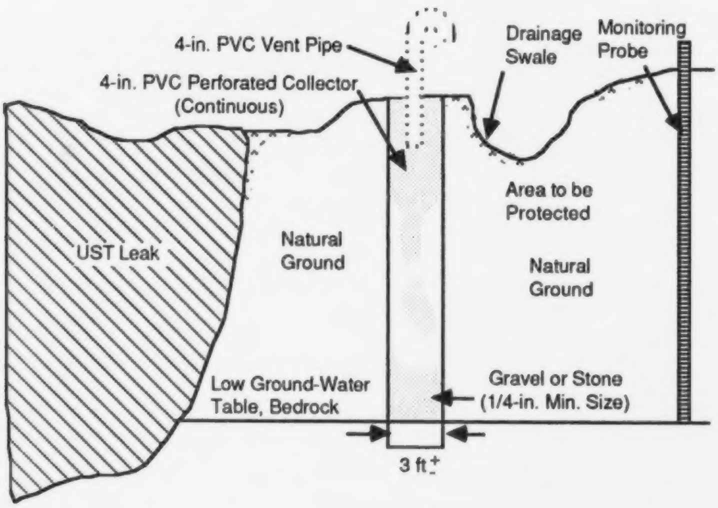
Trenches excavated for passive vapor control systems are normally cut with backhoes; however, other conventional trenching equipment capable of providing adequate depth and width could be used. Rounded gravel or crushed stone (washed of fines) should be used for venting trench backfill material, and only rounded gravel should be used as a permeable medium in conjunction with a synthetic membrane liner to avert tearing or puncturing the membrane. Although virtually any pipe material can be used for perforated and riser pipe, the use of 3- or 4-inch PVC pipe is customary. Polyvinyl chloride (PVC), polyethylene (PE), chlorinated polyethylene (CPE), Hypalon, and other materials have been used for impermeable synthetic membranes. A minimum thickness of 20 mils is recommended. Lap joints are cemented or heat-welded and may be made at the factory or in the field.

During trench excavation for passive systems, care should be taken to ensure that workers are not overcome by venting vapors or exposed to explosion hazards. Open flames and smoking should be prohibited in the work area. Regular monitoring of gasoline, methane, oxygen, and other vapors of concern

Figure 5-56. High-permeability passive vapor control system

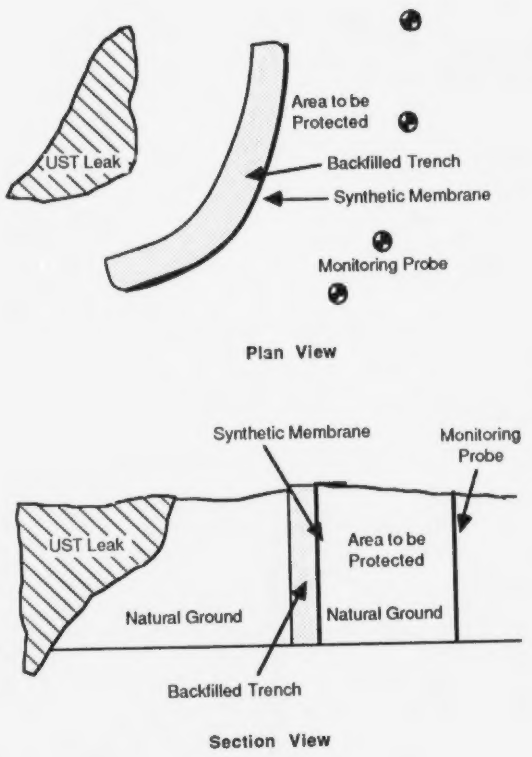

Permeable Vent Trench
UST Leak
Area to be Protected
Drainage Swale
Monitoring Probe

Plan View


4-in. PVC Vent Pipe
4-in. PVC Perforated Collector (Continuous)
Drainage Swale
Monitoring Probe
UST Leak
Natural Ground
Area to be Protected
Natural Ground
Low Ground-Water Table, Bedrock
Gravel or Stone (1/4-in. Min. Size)
3 ft±

Section View

Figure 5-57. **Low permeability passive vapor control system**



should be conducted. Depending on soil characteristics and trench depth, sloping of trench walls may be required to avoid instability; alternatively, shoring and bracing can be used to support trench walls. This does not adversely affect the installation; however, additional backfill material is required. During the installation of synthetic membrane barriers, extreme care must be taken to ensure that lap joints are properly sealed and that tears and punctures are averted in the process of placing the membrane and backfilling the trench.

Monitoring the effectiveness of passive vapor-control systems normally consists of periodic sampling of subsurface vapors from probes installed in the area being protected. Installation of a vapor-monitoring probe requires the drilling of a hole in the soil to a depth above which monitoring is desired. A probe pipe, which is perforated except for the upper several feet, is installed in the drilled hole, and the hole is backfilled with permeable material (sand or pea gravel) to a height above the perforations. The remainder of the hole is backfilled with soil, which acts as a seal to prevent the intrusion of air. (Seals are sometimes used to keep this soil from entering the permeable material.) A vapor sample can then be withdrawn from the probe at the surface.

5.8.1.4 Costs

Because the lengths, depths, and widths of passive system trenches vary, the unit cost per linear foot of landfill border will be totally site-specific. The capital costs in Table 5-32 are given in units that can be readily determined for a given site, with some judgment on the part of the estimator. Costs shown are based on the following particulars:

- Trench depth of 30 feet; length 2500 feet; width 3 feet.
- Collector piping installed over whole length of trench with vent pipes 10 feet long and spaced at 50 feet.
- Vapors vented to atmosphere.
- Monitoring probes spaced at 100 feet, each 30 feet deep.

Table 5-32. **1986 Unit Costs for Components of Passive Vapor-Control Systems***

Item	Cost Range ($)
Excavation and disposal of material	2 to 4/yd^3
Gravel backfill	12 to 18/yd^3
Bank sand backfill	6 to 9/yd^3
Piping	4 to 6/ft^2
Synthetic membrane	2 to 4/ft
Monitoring probes	10 to 15/ft

* Data from EPA 1985a.

5.8.2 Active Vapor Control (EPA 1985a)

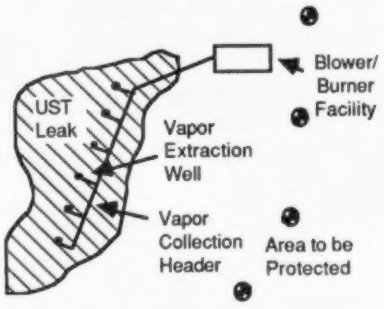
5.8.2.1 General Description

Subsurface vapor migration also can be controlled by active vapor-control systems, which consist of vapor extraction, vapor collection headers, vacuum blowers or compressors, and/or vapor treatment or utilization systems (Figure 5-58).

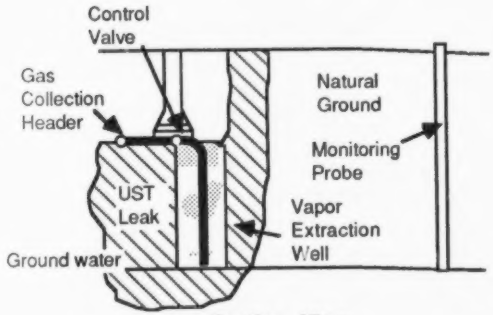
Blowers or compressors establish a pressure gradient through collection headers and wells to the area surrounding the plume. The subsurface vapors then flow through the collection system to the treatment or recovery system.

The use of forced-air venting can also significantly lower gasoline vapor concentrations in the soil above

Figure 5-58. **Active vapor control system (EPA 1985a)**



Plan View



Section View

an underground gasoline release and can also remove some gasoline from the underground environment. This relatively simple system consists of an air intake and air exhaust system to force air through the soil medium. Only experimental data are currently available; however, this looks like a promising means of reducing vapors resulting from medium to large releases of petroleum or petroleum products.

5.8.2.2 Application/Availability

Active vapor-control systems can be used at any site where the needed excavation can be made for their installation. Systems of extraction wells, control trenches, and header piping are normally required, along with vapor pumping and disposal equipment. Active vapor-control systems are not sensitive to the freezing or saturation of surface or cover soils.

5.8.2.3 Design and Construction Considerations

Active vapor-control systems consist of several components, all of which require different materials of construction and installation techniques. Table 5-33 summarizes the major requirements. Specific material selection is at the discretion of the designer; however, the materials listed are those that experience has proven to perform satisfactorily. Corrosion resistance, flexibility, and ease of installation are of particular importance in the selection of materials and the design of the components for these systems, which generally will be somewhat temporary (i.e., expected system life is but a few years).

Approximate values for design criteria should be determined by vapor extraction tests on one or more test wells, during which the change in pressure gradient radially from the wells should be monitored. Other parameters that should be monitored during the tests are vapor extraction flow rates, subsurface negative (vacuum) pressures at various depths and distances from the well(s), and negative pressures within the well.

In general, vapor extraction wells should be constructed before a header pipe is installed because wells are often relocated in the field during construction for a variety of reasons and realignment of header configurations may be desirable. Blower/burner facility construction usually may begin at any time because its location is dictated by factors of accessibility. Associated header alignments may be adjusted to accommodate the facility.

The first step in designing a vapor-collection header is to estimate vapor flow rates from the individual extraction wells. Preliminary flow rate estimates may be inaccurate; therefore, a factor of safety should be used to adjust the flow rate upward. Cumulative vapor flow rates along the header line are estimated by summing the individual well flow rates "upstream" from the point under consideration.

Blower capacity or extraction wells can readily be added to existing active systems to improve performance. Shutdown and other nonperformance alarms can be provided to identify the need for emergency maintenance, which increases reliability. Regular operation and maintenance of mechanical systems (motors, bearings, belts, etc.) is required on all active systems.

Active vapor-control systems can be implemented with relatively conventional equipment, labor, and materials. Some mechanical equipment may require delivery lead times of several months. Well drilling is accomplished with caisson, auger, and bucket rigs. A few systems having high-torque capacity also are needed to excavate through large obstacles that may be present. Pipe laying is similar to utility pipeline construction.

Implementation of active vapor control systems requires little time. Several wells can be completed by a single crew in a day (equivalent to several hundred feet of perimeter per day), and collection piping and mechanical components can be installed concurrently. Vapor control can be effected upon completion and startup, and immediate results (as measured in monitoring probes) are realized.

Table 5-33. Materials and Equipment for Active Vapor-Control Systems[*]

Item	Materials	Installation
Well drilling	-	Auger, caisson, or bucket drill rig
Well piping	2- to 6-in. PVC, schedule 40 to 80, perforated and solid-wall	Crane for deep wells, backhoe for shallow wells
Well backfill	1-in. washed crushed stone or river gravel	Placed slowly by hand
Header piping	3-in. or greater (depending on flow/ pressure requirements) PVC, polyethylene, or fiberglass (resistant to chemical attack)	Conventional trench excavating equipment, specialized jointing equipment for some pipe materials
Valves	Compatible with pipe size; gate, ball, or butterfly type; PVC or other chemical-resistant material	Jointing similar to piping materials
Vacuum blower	Material or coating that resists chemical attack; size varies with flow/pressure requirements	Foundation and installation per manufacturer recommendations
Safety devices	Specific items manufactured for use at refineries, sewage digestors, etc.	Installed with piping
Vent stacks	Any corrosion-resistant pipe of adequate size and strength; may require support	Same as header piping

[*] Data from EPA 1985a.

5.8.2.4 Costs

The capital costs of active vapor-control systems vary greatly and depend on the size and depth of the plume, the nature of the contaminant, and the selected design criteria. Table 5-34 shows unit costs for typical components of a vapor-control system. The large range of units costs is due to the variable nature of the system, which depends on the characteristics of the plume in question. Unit costs for deep extraction wells will be greater than those for shallower wells because more specialized equipment is needed. Likewise, large-diameter header pipe is more costly than smaller pipe because material and labor costs are higher. Blower/treatment facilities may vary in scale from a small blower with a vent stack to multiple, high-volume blowers with or without multiple and/or high-volume burners, automatic timers, valves, switches, and recorders.

Annual operating and maintenance costs also vary with the size of the system. For example, a blower driven by a 5-horsepower motor operating continuously will consume about $2000 to $3000 worth of electricity at 5 cents/kilowatt-hour. Other electrical costs for lighting or automatic controls are nominal in comparison. The cost of replacement parts also should be small because the system has few mechanical components. Small material costs can be expected for tools, lubrication, replacement of belts, fuses, etc. Manpower costs, assuming an average of two or three person-days per month on a contract basis, should be on the order of $5000 annually; the

Table 5-34. 1986 Unit Costs for Components of Active Vapor-Control Systems[*]

Item	Range of Unit Costs ($)
Vapor-extraction well (drilling, stone, piping, etc.), in place	50 to 80/vertical foot
Well connection lateral (10-ft piping valve, excavation, fittings, etc.), in place	1,000 to 1,550 each
Vapor-collection header (piping, excavation, fittings, etc.), in place	20 to 105/linear foot
Blower facility (blower(s), safety devices, valves, foundation, piping, fencing, electrical components, and service connection), in place	50,000 to 105,000 (total)
Monitoring probe (drilling, pipe, fittings, backfill, etc.), in place	10 to 15/vertical foot
Operation and maintenance	5,000 to 20,500/year
Monitoring with portable meter	10 to 15 each visit

[*] Data from EPA 1985a.

costs will vary with the scale and sophistication of the system. Other annual costs that may be considered are insurance, security, interest, and administration or overhead.

5.8.3 Ventilation of Structures

5.8.3.1 General Description

Leakage from underground storage systems can affect subsurface structures when the leaking compound volatilizes and the vapors penetrate basement walls, sewer systems, manholes, conduits, drains, etc., that are not constructed of impervious materials. The condition created by the existence of vapors in underground structures can be grouped into two classes: 1) flammable, and 2) injurious to life. The latter condition results from the toxic or suffocating properties of the vapors (NFPA 1982). When these conditions arise, steps must be taken to ventilate the affected structure to remove the hazardous condition.

5.8.3.2 Application/Availability

The first symptoms of a hydrocarbon loss often are manifested in the form of vapors, which result from the volatilization of a portion of the fugitive organic product. These vapors usually are more noticeable during periods of the year when soil conditions are wet from prolonged rains and when frost is in the ground. Both of these conditions form an impermeable cap that causes the vapors to seek other avenues for venting to the surface, such as utility conduits or building basements. Because these vapors often have the potential to reach combustible levels, their presence usually elicits public demand for immediate attention (Yaniga 1984).

Ventilation systems and equipment for remedying the situation are readily available for installation by experienced heating/ventilating/air conditioning contractors. Local fire departments are a source of ventilating equipment for emergency situations and could be a reference to other local industrial sources. Tool rental agencies also carry ventilation equipment that can be obtained quickly and will suffice until more suitable models or remedies are available.

5.8.3.3 Design and Construction Considerations

Whereas the best long-term method for vapor abatement is to recover or neutralize the fugitive contaminants, it is sometimes necessary to abate the symptoms quickly so that imminent danger to the public is minimized. Three general methods are available to address symptomatic vapor problems:

1) The first and most common method is to ventilate the affected structure(s) so that the atmosphere is exchanged or cleansed, either continuously or on command. This method is effective, but it can raise the cost of heating or cooling the structure beyond the point of economic feasibility. This approach also has the tendency to induce vapor movement into the structure by creating a negative pressure to which vapors will migrate.
2) Another approach that has been used successfully involves the induction of a positive pressure within the structure that inhibits the inflow and accumulation of vapors. This is accomplished by adding a volume of makeup air to the structure that is greater than its collective air loss. This makeup air is seasonally heated and cooled as necessary.
3) The third approach involves the forced ventilation of vapors from soils before they can accumulate within the structure. This is accomplished by installing horizontal or vertical collection pipes below grade and connecting them to a high vacuum pump that pulls the vapors to a central area for safe venting and/or destruction (see Subsection 5.8.2).

The preferred approach to addressing vapor mitigation in buildings is a combination of methods 2 and 3 (Yaniga 1984b).

The objective in ventilating the vapor-contaminated space is to dilute the atmosphere so the concentration of the contaminant in the air is below its lower explosive limit (LEL) or below its threshold limit value (TLV). Instrumentation will be necessary to detect these properties, and a system or routine should be established for monitoring them.

Any ventilating equipment should be equipped with explosion-proof motors and switch gear. Particular caution should be exercised to deenergize or render harmless any ignition sources that may be present in vapor-contaminated space (e.g., vapor-fired heaters, light switches, nonexplosion-proof motors, and electrical items).

5.8.3.4 Costs

Remedial action for the situations discussed will be very site-specific; therefore, representative cost figures cannot be presented here. Emergency ventilating fans can be rented for between \$10 and \$20 a day; more suitable ducted blowers with makeup heaters and controls may cost \$1000 to \$5000, installed.

5.8.4 Adsorption

5.8.4.1 General Description

Vapors collected at an UST leak site can be treated by adsorption, a process for transferring and concentrating contaminants from one medium to another. The most commonly used adsorbent is activated carbon; other adsorbents are specially manufactured resins.

Adsorber systems consist of ducting or piping and a blower for moving the contaminated air and a vessel(s) that contains the adsorbent. In practice, the contaminated air is blown through the adsorber vessel, where the contaminant is removed.

5.8.4.2 Application/Availability (EPA 1985a)

Carbon adsorption can be used to treat vapors containing volatile hydrocarbons and most halogenated organics. It can also control oxides of sulfur and nitrogen and carbon monoxide. Resins are capable of removing most organic contaminants from gaseous streams; however, they are not widely used in this application.

Vapor flow rate and influent and discharge adsorbate concentrations must be monitored to determine changeover/regeneration schedules. Automatic monitors and microprocessors may be warranted for highly complex and variable systems. Alarms and/or shutdown controls may also be warranted for complex systems or in sensitive or populated areas.

5.8.4.3 Design and Construction Considerations (EPA 1985a)

Adsorption techniques are well established for removal of organic compounds and some inorganic compounds from gaseous streams. Adsorption is highly reliable if adsorbates and adsorbent are properly matched, sufficient contact time is allowed, and the adsorbent is regenerated or replaced before saturation (and desorption) is reached. Many adsorption systems are prepackaged and can be quickly installed and put into operation by contractors, suppliers, or manufacturers. Specially designed systems use off-the-shelf towers, blowers, and other equipment and require additional installation time.

Operation of properly designed adsorption vapor-treatment systems is essentially as automatic as the vapor-delivery system; however, manual or special automatic adjustments may be needed for highly variable flows or adsorbate concentrations. Changeover or regeneration of the adsorbent bed must be conducted on a predetermined basis to ensure continuous effective treatment.

Multiple-bed vessels are often required to allow adequate contact time to optimize the frequency of adsorbent changeover or regeneration. Partial or total redundant capacity is often provided by extra bed vessels to allow continuous operation during changeover or regeneration.

Spent adsorbents can be disposed of in appropriate landfills, incinerated, or can be regenerated. Regeneration drives off the adsorbate and allows the adsorbent to be reused for treatment. Granular activated carbon is regenerated by heating it in a reduced-pressure atmosphere. Resins are regenerated by washing them with appropriate solvents. Adsorbed materials (e.g., solvents) can be recovered from the regeneration process and reused.

5.8.4.4 Costs

Capital and operating costs for an adsorption system are highly dependent on the specific system type, vapor flow volumes, and the contaminant concentrations to be treated.

Direct capital costs can be estimated by the equation:

$$DC = 8.3\,(Q) + 34$$

where

DC = Direct capital costs, $1000's

Q = Vapor flow rate, 1000 cfm
(300 cfm $\leq Q \leq$ 10,000 cfm)

Operation/maintenance costs can be estimated by the equation:

$$OM = 12.2\,(Q)$$

where

OM = Annual operating and maintenance costs, $1000 per year
(These include maintenance, power, makeup carbon, and spent carbon hauling/disposal.)

Q = Vapor flow rate, 1000 cfm
(300 cfm $\leq Q \leq$ 10,000 cfm)

5.8.5 Flaring

5.8.5.1 General Description

Flaring is a special category of combustion in which vapors are exposed to an open flame; no special features are used to control temperatures or time of combustion. It is a means of disposing of vapors that are easily burned and have no harmful products of combustion. Supplementary fuels may be needed to sustain continuous combustion.

5.8.5.2 Application/Availability

Flares are commonly used in the oil industry to dispose of waste vapors and fumes at refineries; at sewage treatment plants to dispose of digestor vapors; and at sanitary landfills to dispose of landfill vapors. Flaring is applicable to gaseous waste streams consisting of relatively simple hydrocarbons, such as vapors from fuel tanks (EPA 1985a).

Flaring may be a suitable technology for disposing of vapors ventilated from a subsurface structure if they are burnable and venting them directly to the atmosphere is not feasible. Properly designed and operated, flares pose no unusual safety impacts to operators or others. The public sometimes considers the presence of a visible flame to be a nuisance.

5.8.5.3 Design and Construction Considerations (EPA 1985a)

Flaring systems, by virtue of their relative lack of controllability, are generally considered to be inconsistent in performance. They are relatively simple to fabricate and to install. Conventional steel plate, pipe, and welding are used in fabrication.

Supplemental fuel is required to sustain a flame when vapors have a very low heating value; however, vapors with heating values as low as a few hundred Btu per cubic foot can sustain a flame (natural gas has a heating value of approximately 1000 Btu per cubic foot).

Flame sensors, pilot flames, automatic sparkers, and alarms are often used to detect loss of flame, to attempt reignition, and to alert operators to system performance problems. Shields can be strategically placed as windbreaks to prevent the flame from being "blown out."

The flow rate dictates the diameter and height of the flare and the number of flares required. The flare must be designed so that the flame is largely contained within the body of the flare for safety reasons and to allow adequate mixing of vapor and air. The oxygen content of the vapor influences the air/gas ratio that is sought in the combustion area of the flare.

A blower usually moves the waste vapor to the flare through piping, a moisture knockout pot, and a stack. The maximum allowable pressure drop is approximately 60 in. H_2O for the system.

5.8.5.4 Costs

Operating costs for flares are high because substantial quantities of natural gas and steam (in the smokeless type) are consumed. If the waste gas must be driven, fan power costs for overcoming pressure drops also may be high.

The capital costs of flare systems depend primarily on the waste-gas flowrate, and secondarily on design and elevation. The typical costs listed in Table 5-35 include ladders, platforms, knockout drums with seals, and stacks high enough to ensure grade-level radiation no greater than 1500 Btu/(h) (ft^2). These costs represent self-supporting type elevated flares approximately 40 feet high. Costs of elevated flares supported by guy wires (nominally 100 feet tall) range from 30 percent higher (as opposed to the self-supporting type) at flow rates of 250,000 lb/h to 80 percent higher at flow rates of 2500 lb/h.

Table 5-35. 1986 Capital Costs of Elevated Flares (for vapor with heat content of 60 Btu/ft^3)*

Waste Vapor Flow Rate (lb/h)	Cost ($)
3,000	7,200
10,000	9,800
50,000	10,700
100,000	11,000

* Data from Vatavuk and Neveril 1983, updated to 1986.

Elevated flares require supplemental fuel (in addition to gas for pilots and purging) when a low-Btu vapor is being burned. The required supplemental fuel (natural gas), based on 880 h/yr operation, is listed in Table 5-36.

Table 5-36. Supplemental Fuel Requirements for Elevated Flares*

Waste Vapor Flow Rate (lb/h)	Natural Gas (10^6 Btu/yr)
3,000	3,800
10,000	12,000
50,000	55,000
100,000	110,000

* Data from Vatavuk and Neveril 1983.

Steam consumption for smokeless flares (or others requiring steam injection) is estimated to be 0.6 lb of steam per pound of vapor.

5.9 Surface Water/Drainage Controls (EPA 1985a)

Surface-water/drainage controls most applicable to UST releases include diversion and collection systems, grading, capping, and revegetation, which are designed to minimize contamination of surface waters, to prevent surface-water infiltration, and to prevent offsite transport of surface waters that have been contaminated. The following is a list of the methods and technologies required for each control activity.

- Prevention of run-on/interception of runoff: The following technologies are used to divert or intercept surface water. Technologies that are designed to prevent or reduce run-on include dikes, diversion channels, flood walls, terraces, grading, and revegetation. Temporary diversion dikes, diversion channels, and terraces are constructed upslope of a site to direct run-on from offsite to a collection system or away from the site. Terraces are used in combination with dikes or ditches to channel water stopped by the terraces away from the site.

- Prevention of infiltration: The primary method for preventing infiltration of onsite surface water is capping. Grading also helps to minimize infiltration by maximizing the amount of water that will run off without causing significant erosion. Revegetation can either promote or minimize infiltration.
- Collection and transfer of water: The following technologies are used to collect diverted water and discharge or transfer it to storage or treatment. Chutes (or flumes) and downpipes are designed to transfer water away from diversion structures such as dikes or terraces to stabilized channels or outlets. Waterways can be used to intercept or divert water as well as to collect and transfer water diverted elsewhere.
- Storage and discharge of water: Technologies for this purpose include seepage basins and ditches, sedimentation basins, and storage ponds. Their function depends on the level of contamination of the water they receive. Seepage basins and ditches are used to discharge uncontaminated or treated water down and away from the site. Sedimentation basins are used to control suspended solid particles in surface-water flow.

The most effective strategy for managing surface flow is often a combination of several control technologies. Table 5-37 summarizes the major surface water controls and indicates their general function.

5.9.1 Diversion/Collection Systems

5.9.1.1 General Description

This section addresses the various surface water diversion and collection methods. These include dikes and berms, channels and waterways, terraces and benches, chutes and downpipes, seepage basins and ditches, and sedimentation basins and ponds. Each is addressed separately in the following two subsections.

5.9.1.2 Application/Availability

Dikes and Berms

Dikes and berms are temporary structures used to prevent excessive erosion of newly constructed slopes until more permanent drainage structures are installed or until the slope is stabilized with vegetation. These structures are frequently used to provide temporary isolation of wastes prior to removal or effective containment. Their use is especially widespread during excavation and removal operations where it is necessary to isolate contaminated soils that have been temporarily staged on site. These temporary structures are designed to handle relatively small amounts of runoff; they are not recommended for drainage areas larger than 5 acres. Diversion of

Table 5-37. Summary of Surface Water/Drainage Controls*

	General Function			
Technology	Prevent or Intercept Run-on/Runoff	Prevent or Minimize Infiltration	Collect and Transfer	Store and Discharge
Capping		x		
Grading	x			
Revegetation	x	x		
Dikes and berms	x			
Channels and waterways			x	
Terraces and benches	x			
Chutes and downpipes			x	
Seepage basins and ditches				x
Sedimentation basins and ponds	x			x

* Data from EPA 1985a.

storm runoff will decrease the amount of water available to infiltrate the soil cover.

Channels and Waterways

Channels and waterways are excavated ditches, usually wide and shallow, with trapezoidal, triangular, or parabolic cross sections. They are used primarily to intercept runoff or slope length, and they may or may not be stabilized. Channels stabilized with vegetation or stone rip-rap are used to collect and transfer diverted water offsite or to onsite storage or treatment.

Terraces and Benches

Terraces and benches are embankments constructed along the contour of very long or very steep slopes to intercept and divert flow and to control erosion by reducing slope length. These structures are classified as bench terraces or drainage benches. Bench terraces are used primarily to reduce land slope, whereas drainage benches on broad-based terraces are used to remove or retain water on sloping land.

Chutes and Downpipes

Chutes and downpipes are structures used to carry concentrated flows of surface runoff from one level to a lower level without erosive damage. They generally extend downslope from earthen embankments (dikes or berms) and convey water to stabilized outlets located at the base of terraced slopes.

Chutes and downpipes often represent key elements in combination surface control systems. They are especially effective in the temporary prevention of erosion on long, steep slopes, and they can be used to channel storm runoff to sediment traps, drainage basins, or stabilized waterways for offsite transport. Chutes are limited to heads of about 18 feet or less, and downpipes are limited to drainage areas up to 5 acres in size. These structures provide a quick solution for emergency situations on which downslope ditches or waterways overflow during severe storms and threaten to erode the base of disposal fill areas.

Seepage Basins and Ditches

Seepage or recharge basins and ditches are used to discharge water collected from surface water diversions and ground-water pumping or treatment. They may also be used in in situ treatment to force treatment reagents into the subsurface.

Seepage basins and ditches are most effective in highly permeable soils so that recharge can be performed. They are not applicable at sites where collected runoff or ground water is contaminated. Basins and ditches are normally used in areas with shallow ground-water tables, as very deep basins or trenches can be hazardous.

Sedimentation Basins and Ponds

Sedimentation basins are used to control suspended solids entrained in surface flows. A sedimentation basin is constructed by placing an earthen dam across a waterway or natural depression, by excavation, or by a combination of both. The purpose of a sedimentation basin is to impede runoff containing solids, and thus to allow sufficient time for the particulate matter to settle.

Sedimentation basins are usually the final step in the control of diverted, uncontaminated runoff prior to its discharge. They are especially useful in areas where the runoff has a high silt or sand content. They are an essential part of any good surface flow-control system.

5.9.1.3 Design and Construction Considerations

Dikes and Berms

Dikes and berms ideally are constructed of erosion-resistant, low-permeability, clayey soils. Compacted sands and gravel, however, may be suitable for interceptor dikes and berms. The general design life of these structures is generally no more than one year; however, seeding and mulching or chemical stabilization of dikes and berms may extend their life expectancy. Stabilization with gravel or stone rip rap immediately upslope of diversion dikes will also extend performance life.

The techniques for constructing dikes and berms are well-established, and the necessary excavation and grading equipment is frequently already available at the disposal site. The required earthfill is often available on site as well.

Channels and Waterways

As an alternative to excavated ditches, channels can be constructed of half-round pipe. The pipe can be constructed of cut corrugated metal pipe (CMP), or sectional slope drains made of asbestos-impregnated asphalt can be purchased for this purpose. The channels are formed by placing the half-round pipe below ground. This type of channel is easier to install than earthen channels, and maintenance costs are lower. In addition, they decrease infiltration into the site. Like earthen channels, half-round pipe channels may be constructed on the perimeter of an UST site and moved as needed to protect other portions of the site. They also are effective for carrying storm water runoff over a filled area when it is not practical to divert the runoff around the fill.

Channels and waterways should be designed to accommodate flows resulting from 10- or 25-year rainfall events (storms). More importantly, they should be designed and constructed to intercept and convey such flows at nonerosive velocities. The design of channel and waterways is generally based on the Manning formula for steady uniform flow in open channel.

Terraces and Benches

Although benches and terraces are slope-reduction devices, they are generally constructed with reverse or natural fall. Diversions and ditches included in bench/terrace construction may be seeded and mulched, sodded, or stabilized with riprap or soil additives. Stabilization may include any combination of these methods. Lining the channels with concrete or grouted riprap is a more costly alternative.

In the design of a terrace system, proper spacing and location of terraces and providing a channel with adequate capacity are major considerations. The spacing between benches and terraces will depend on the length and steepness of the slope and the type of soil. In general, the longer and steeper the slope and the more erodible the cover soil, the less the distance should be between drainage benches to maximize erosion reduction. For slopes with steepness greater than 10 percent, the maximum distance between drainage benches should be approximately 100 feet, i.e., one bench for every 10 feet of rise in elevation. When the slope is greater than 20 percent, one bench should be placed for every 20 feet of rise in elevation.

Benches and terraces are constructed with a variety of commonly used excavation equipment including bulldozers, scrapers, and graders. The usual well-established techniques are applied, and local fill material is used. Benches and terraces must be sufficiently compacted and stabilized with appropriate vegetation to accommodate local topography.

Chutes and Downpipes

Chutes and downpipes can be constructed quickly and inexpensively. No special materials or equipment are required. Temporary downpipes may be constructed by joining half-round sections of bituminous fiber or concrete pipe. These structures provide a quick solution for emergency situations when downslope ditches or waterways overflow during severe storms and threaten to erode the base of disposal fill areas.

Seepage Basins and Ditches

Considerable flexibility is possible in the design of seepage basins and ditches. A seepage basin typically consists of the basin itself, a sediment trap, a bypass for excess flow, and an emergency overflow. Because a considerable amount of recharge occurs through the sidewalls of a basin, the use of a previous material of construction is advisable. Gabions are frequently used to make sidewalls.

Well-established techniques and procedures are used in the construction of seepage basins and ditches. Much of the necessary equipment and material will be found on site. Such things as piping and gravel may have to be ordered, but they should be readily available.

Dense turf on the side slopes of these basins will not only prevent erosion and sloughing, but will also allow a high infiltration rate. Prevention of scouring by the inlet is an important consideration to reduce maintenance requirements. This can be accomplished by use of a "hydraulic jump" or an impact stilling basin before the water flows into the recharge basin. Percolation can be improved by construction of gravel-filled trenches along the basin floor.

Sedimentation Basins and Ponds

The removal of suspended solids from waterways is based on the concept of gravitational settling of the suspended material. A typical design for a sedimentation basin embankment includes a principal and emergency spillway, an antivortex device, and the basin. The principal spillway consists of a vertical pipe or riser jointed to a horizontal pipe (barrel) that extends through the dike and outlets beyond the water impoundment. The riser is topped by an antivortex device and trash rack that improve the flow of water into the spillway and prevent floating debris from being carried out of the basin. The riser should be watertight and, except for a dewatering opening at the top, should be free of holes, leaks, or perforations. The riser base should be attached to a watertight connection, and it should weigh enough to prevent the riser from floating. The water discharged from the sediment basin through the principal spillway should be conveyed in an erosion-free manner to an existing stable stream.

Before construction begins, the areas under the embankment and any structural works should be cleared, grubbed, and stripped of topsoil to remove trees, vegetation, roots, or other objectionable material. Fill material for the embankment should be clean mineral soil, free of roots, woody vegetation, oversized stones, rocks, or other objectionable material. Areas should be scarified before they are filled. The moisture content of the fill material should be high enough to permit the material to be formed by hand into a ball without crumbling. This will facilitate proper compaction. Compaction is obtained by routing the hauling equipment over the fill in such a manner that the entire surface of the fill is traversed by at least one wheel or tread track of the equipment, or by using a compactor.

The riser of the principal spillway should be securely attached to the barrel by a watertight connection, and the barrel and riser should be placed on a firmly compacted soil foundation. The base of the riser should be firmly anchored to prevent floating. Pervious materials such as sand, gravel, or crushed stone should not be used as backfill around the barrel. At least 2 feet of fill material should be placed around the pipe in thin layers and compacted by hand at least to the same density as the embankment before it is crossed with construction equipment.

5.9.1.4 Costs

Costs for surface water diversion/collection structures include those for ditch linings, riprap slope protection, soil testing, corrugated metal pipe, sheet piling, backflow valves, and sumps. Table 5-38 summarizes these unit costs and the structures to which they apply.

All cost estimates should be determined on a site-specific basis and be based on the specific structures to be installed, all associated earthwork, and any special appurtenances that may be required. A general methodology for estimating costs for construction of surface-water diversion/collection structures should contain the following elements:

- Source of required earth fill (onsite vs. offsite) and hauling distances.
- Amount of fill required (cubic yards).
- Type and quantity of other materials required (cubic yards of pipe, square feet of riprap, etc.).
- Costs of installation or placement of these materials (using unit costs).
- Costs of required stabilization for earthen structures (berms, etc.) based on the area (in square yards) to be stabilized; revegetation, riprap, or gravel stabilization.
- Required maintenance or repair costs for a given time period based on reasonable assumptions; for example, assuming the diversion requires rebuilding (new fill and compaction) twice a year, after major storms, costs will be...
- Summation of all calculated costs to arrive at the total estimated construction and maintenance expenditures.

Costs are derived by simply multiplying unit costs shown in the table by the required quantities of the material or service. These costs will give gross estimates only; they are to be used as general guidelines for the decision-maker in evaluating alternative strategies.

5.9.2 Grading

5.9.2.1 General Description

Grading is the general term applied to techniques used to reshape the land surface to manage surface-water infiltration and runoff and to control erosion. The required spreading and compaction steps are techniques practiced routinely by earthwork contractors. The equipment and methods used in grading are essentially the same throughout the country, but their application will vary by site. Grading is often performed in conjunction with surface sealing and revegetation as part of an integrated site-closure plan.

5.9.2.2 Application/Availability

The techniques and equipment used in grading operations are well established and widely used in all forms of land development. Contractors and equipment are usually available locally, which expedites the work and avoids extra expenses.

5.9.2.3 Design and Construction Considerations

Grading is used to modify the natural topography and runoff characteristics of a site and thereby to control infiltration and erosion due to surface water. Continuous grades are established to ensure that runoff water does not pond. The choice of specific grading techniques for a given site will depend on the desired site-specific functions of a graded surface. A graded surface may reduce or enhance infiltration and detain or promote runoff.

Erosion control may be considered a complicating variable in the design and performance of a grading scheme. The design of graded slopes at sites should balance infiltration and runoff control against possible decreases in slope stability and increases in erosion. The design of specific slope configurations, the choice of cover soil, the degree of compaction, and the types of grading equipment used will all depend on local topography, climate, future land use, and drainage methods.

All States and localities publish guidelines and regulations for performance of any grading work. These publications should be consulted before a grading system is designed.

The equipment used to construct graded slopes consists of both standard construction and specialized earth-moving vehicles. Excavation, hauling, spreading, and compaction of cover materials are the major elements of a complete grading operation. Grading vehicles include scrapers, crawler bulldozers and loaders, rubber-tired bulldozers and loaders, and compactors.

It is important that grades be constructed in accordance with design specifications. Particular attention should be given to the backfill and compaction methods used by the contractor. Normally, compaction is achieved through repeated passes of leveling equipment over the area in several different directions. Any compaction tests specified in the design should be performed to assure the permanence and stability of the grading work.

Table 5-38. 1986 Unit Costs Associated With Surface Water Diversion and Collection Structures

Description	Applicable Structures*	Range of Unit Costs ($)	Source†
Excavation, hauling, grading (spreading and compaction)	All	See Table 5-1	
Trench excavation	D/B, D/D/W, BT, L, DT/B		
Loam, sand, and loose gravel 1 to 6 ft deep, 1/2:1 sides		0.86 to 1.03/yd^3	(1)
6 to 10 ft deep		0.86 to 1.02/yd^3	(1)
Compacted gravel and till 1 to 6 ft deep, 1/2:1 sides		0.86 to 1.21/yd^3	(1)
6 to 10 ft deep		0.86 to 1.09/yd^3	(1)
Building embankments; spreading, shaping, compacting	All		
Material delivered by scraper		0.43 to 0.85/yd^3	(1)
Material delivered by back dump		0.91 to 1.35/yd^3	(1)
Placement of ditch liner pipe, 1/3 section	D/D/W, DB, CD		
15-in. radius		15/ft	(1)
18-in. radius		21/ft	(1)
24-in. radius		31/ft	(1)
Catch basin sump, 3 ft x 4 ft x 1.5 ft	L, DT/B	224 each	(1)
Corrugated galvanized steel underdrain pipe, asphalt-coated, perforated	DT/B		
12-in. diameter, 16-gauge		22/ft	(1)
18-in. diameter, 16-gauge		31/ft	(1)
Corrugated galvanized metal pipe, with paved invert	C/C, SB		
18-in. diameter, 14-gauge		35.04/ft	(1)
36-in. diameter, 12-gauge		89.17/ft	(1)
48-in. diameter, 12-gauge		66.88/ft	(1)
Steel sheet piling	L (seepage control)		
15 ft deep, 22 lb/ft^2		10.94/ft^2	(2)
20 ft deep, 27 lb/ft^2		12.68/ft^2	(2)
25 ft deep, 38 lb/ft^2		16.12/ft^2	(2)
Backflow preventer; gate valves, automatic operation, flanged, 10-in. diameter	L (drainage control)	9,500 each	(2)
Floating baffles	SB	15 to 51/ft	(3)

Table 5-38. (Continued)

Description	Applicable Structures[*]	Range of Unit Costs ($)	Source[†]
Sump pumps, 10-ft head, automatic	L (backwater drainage)		
Bronze		25 to 520 each	(2)
Cast iron		150 to 300 each	(2)
Revegetation, mulching, maintenance	D/B, D/D/W, BT, L	See Table 5-40	
Loose gravel, excavation, loading, hauling 5 miles, spreading, and compacting	All (slope protection; drainage)	8 to 8.75/yd^3	(1)
Stone riprap; dumped from trucks, machine-placed	All (slope protection; channel and outlet stabilization)	22/yd^3	(2)
Soil testing	All (preconstruction evaluation)		
Liquid and plastic limits		31/test	(2)
Hydrometer analysis, specific gravity		51/test	(2)
Moisture content		7.35/test	(2)
Permeability		67/test	(2)
Proctor compaction		110 to 125/test	(2)
Shear tests			
Triaxial shear		150 to 290/test	(2)
Direct shear		100 to 270/test	(2)
Temporary diversion dike	D/B	1.35 to 2.69/linear ft	(4)
Temporary sediment construction, drainage area			
1 to 25 acres		405 to 2,138	(4)
50 to 75 acres		4,048 to 6,645	(4)
75 to 100 acres		6,645 to 8,565	(4)
100 to 125 acres		8,565 to 11,208	(4)
Sediment removal from basins	SB	4.05 to 9.35/yd^3	(4)
Paved flume, installed	C/D, SB	27 to 41/yd^2	(4)
Level spreader construction	D/B, D/D/W, BT, C/D	3.32 to 6.64/linear ft	(4)

[*] Key: D/B = dikes and berms; D/D/W = ditches, diversions, and waterways; BT = bench terraces; CD = chutes and downpipes; L = levees; DT/B = drainage trenches and basins; SB = sediment basins; DB = drainage benches.

[†] Data from (1) McMahon 1984; (2) Godfrey 1984a; (3) EPA 1985a; (4) Virginia SWCC 1980.

5.9.2.4 Costs

Table 5-39 presents unit costs associated with grading equipment and methods. Costs associated with heavy equipment maintenance (fuel, repairs, etc.) are not addressed. Costs of excavation, hauling, spreading, and compaction will vary with equipment type and size, the cover material being graded, haul distance, support labor required, and unforeseen construction difficulties. These costs are representative of average contractor bid prices for performance of the work and therefore include charges for overhead and profit. All costs are reported in 1986 dollars.

5.9.3 Capping

5.9.3.1 General Description

Capping refers to the process used to cover contaminated materials in place to prevent their contact with the land surface and ground water. The designs of modern caps usually conform to the performance standards in 40 CFR 264.310, which addresses RCRA landfill closure requirements. These standards include minimum liquid migration through the wastes, low-cover maintenance requirements, efficient site drainage, high resistance to damage by settling or subsidence, and a permeability lower than or equal to the underlying liner system or natural soils. These performance standards may not always be appropriate, particularly when the cap is intended to be temporary, in places where precipitation is very low, and when the capped waste is not leached by infiltrating rainwater.

A variety of cap designs and capping materials are available. Most cap designs are multilayered to conform with the aforementioned design standards; however, single-layered designs are also used for special purposes. The selection of capping materials and cap design are influenced by specific factors such as local availability and costs of cover materials, desired functions of cover materials, the nature of the wastes being covered, local climate and hydrogeology, and projected future use of the site in question.

5.9.3.2 Application/Availability

Capping is necessary whenever contaminated materials are to be buried or left in place at an UST release site. Capping also may be performed when extensive subsurface contamination at a site precludes excavation and removal of the soil because of potential hazards and/or unrealistic costs.

Capping is often performed together with ground-water extraction or containment technologies to prevent (or significantly reduce) further plume development. This combined effort reduces the time needed to complete ground-water cleanup operations. Ground-water monitoring wells also are often used in conjunction with caps to detect any unexpected migration of the capped material. A vapor-collection system should always be incorporated into a cap when the capped material is volatile. Surface water control technologies such as ditches, dikes, and berms are also associated with capping, as these structures are often designed to control rainwater drainage from the cap. Two other surface-water

Table 5-39. 1986 Unit Costs Associated With Grading

Description	Unit Cost ($)	Source*
Topsoil (sandy loam) from borrow pits, excavation hauling, spreading, and grading (within 25 miles); labor, materials, and equipment	16/yd^3	(1)
Onsite excavation, hauling, spreading, and compaction of earth (1000- to 5000-ft haul); labor and equipment only	2 to 4/yd^3	(1)
Sandy loam topsoil; material only	2.30/yd^3	(1)
Excavating, hauling 2 miles, spreading and compacting loam, sand, or loose gravel (with front-end loader); labor, material, and equipment	6.85 to 7.00/yd^3	(1)
Grading, site excavation, and fill (no compaction):		
75-hp bulldozer, 300-ft haul	3.50/yd^3	(2)
300-hp bulldozer, 300-ft haul	2.40/yd^3	(2)
Field-density compaction testing of soils	110/day	(1)

* Data from (1) McMahon 1984; (2) Means 1984a.

control technologies--grading and revegetation--are incorporated into multilayered caps.

Availability of capping material is somewhat site-specific because the local soils are typically used with admixtures to form parts of the cap. Synthetic membranes, which are available in varying sizes, can be overlain and spliced in the field. In general, capping should be a readily available technology for any UST release site.

5.9.3.3 Design and Construction Considerations

The primary purpose of a cap is to prevent rainwater infiltration. The two basic designs are multilayered and single-layered. Although multilayered caps are the more common, a single-layered cap may be acceptable when a site is being covered temporarily, in an area where little or no ground water exists, or when continual maintenance of the integrity of a cap cannot be absolutely assured. A vapor collection system should always be included in the design of a cover when there is any indication that the underlying contaminant is volatile.

The design of multilayered caps generally conforms to EPA's guidance under RCRA, which recommends a three-layered system consisting of an upper vegetative layer, a drainage layer, and an underlying low-permeability layer. Single-layered caps can be constructed of various low-permeability materials; however, natural soil admixes are not recommended because they are disrupted by freeze/thaw cycles and exposure to drying causes them to shrink and crack. The most effective single-layer caps are composed of concrete or bituminous asphalt.

Construction considerations for single-layered caps vary depending on the cap materials used (e.g., concrete, asphalt, clay); therefore, appropriate construction guidance should be acquired according to the cap material being considered. The EPA document entitled "Lining of Waste Impoundment and Disposal Facilities," SW-870, contains references for guidance in the construction of caps made of several different materials.

Construction of a multilayered cap typically includes a vegetative layer based on topsoil, a drainage layer composed of sand, and a low-permeability layer formed by a combined synthetic and soil liner system. This type of cap function diverts infiltrating liquids from the vegetative layer through the drainage layer and away from the underlying contaminated materials.

The low-permeability layer of a multilayered cap can be composed of natural soils, admixed soils, a synthetic liner, or any combination of these materials; however, a synthetic liner overlying at least 2 feet of low-permeability natural soil or soil admix is recommended because the synthetic liner allows virtually no liquid penetration for at least 20 years, whereas the soil layer provides assurance of continued protection even if the synthetic liner fails.

5.9.3.4 Costs

The cost of a cap depends on the type of materials selected, the thickness of each layer, and the area to be covered. General material and installation costs for multilayered caps are presented in Table 5-40, which indicates the complexity of this type of capping. In a recent RCRA Part B Permit Application for a 4-acre hazardous waste landfill, the estimated installed cost of a multilayered cap was $5.45/ft^2. The design for this cap included 3 feet of topsoil overlying a 1-foot sand layer overlying 1 foot of compacted clay overlying a 30-mil high density polyethylene (HDPE) liner overlying 2 feet of compacted clay. Filter fabric was specified between the topsoil and sand drainage layer to prevent clogging. Quality control testing of each layer of the cap was included in the installation cost estimates.

On the other hand, a single-layer cap comprised of a sprayed asphalt membrane, as might be more typical for an underground storage system leak situation, might cost $2.33 to 3.96/sq. yd.

5.9.4 Revegetation

5.9.4.1 General Description

The establishment of a vegetative cover is a cost-effective method to stabilize the surface of newly graded and/or capped sites. Revegetation decreases erosion by wind and water and contributes to the development of a naturally fertile and stable surface environment. Also, the technique can be used to restore the appearance of sites following any cleanup operations.

A systematic revegetation plan will include: 1) selection of suitable plant species, 2) seed bed preparation, 3) seeding/planting, 4) mulching and/or chemical stabilization, and 5) fertilization and maintenance.

5.9.4.2 Application/Availability

Grasses such as fescue and lovegrass provide a quick and lasting ground cover, with dense root systems that anchor soil and enhance infiltration. Legumes (lespedeza, vetch, clover, etc.) store nitrogen in their roots, enhancing soil fertility and assisting the growth of grasses. They are also readily established on steep slopes. Shrubs such as bristly locust and autumn olive also provide a dense surface cover, and certain species are quite tolerant of acidic soils and other possible contaminated site stresses. Trees are generally planted in the later stages of site restoration, after grasses and legumes have established a stable ground cover. They help provide long-term protective cover and build up a stable, fertile layer of decaying leaves and branches. A well-mixed cover of grasses,

Table 5-40. 1986 Unit Costs Associated With Capping[*]

Item[†]	Unit Cost ($)
Clearing and grubbing	1,130/acre
Excavation	1.65/yd^3
Earthfill	
Berms and levees	2.15/yd^3
Soil liners	3.20/yd^3
Backfill	3.20/yd^3
Soil import	
Drainage sand	10.80/yd^3
Drainage rock (rounded)	10.80/yd^3
Soil placement	1.05/yd^3
Vegetation, mulch, and hydroseed	1,130/acre
Geotextile fabrics	1.00 to 3.20/yd^2
Bentonite admix (2 to 9 lb/yd^3)[‡]	0.20 to 1.15/ft^2
Membrane liners	
Nonreinforced	
30-mil PVC	0.25 to 0.35/ft^2
30-mil CPE	0.35 to 0.45/ft^2
30-mil Butyl/EDPM	0.45 to 0.60/ft^2
30-mil Neoprene	0.70 to 0.80/ft^2
100-mil HDPE	1.10 to 1.65/ft^2
Reinforced	
36-mil Hypalon (CSPER)	0.50 to 0.65/ft^2
60-mil Hypalon (CSPER)	0.80 to 1.05/ft^2
36-mil Hypalon	0.50 to 0.65/ft^2
Installation, excluding earthwork	0.60 to 1.25/ft^2

[*] Based on costs for a 400,000 ft^2 area presented in Cope, et al., 1984, and updated to 1986 dollars by using the ENR Construction Cost Index.

[†] Key: PVC = polyvinyl chloride; CPE = chlorinated polyethylene; EDPM = ethylene-propylene-eiene-monomer; CSPER = chlorosulfonated polyethylene (reinforced); HDPE = high density polyethylene.

[‡] Includes mixing and placing.

shrubs, and trees will ultimately restore both economic and aesthetic value to a site and will provide suitable habitat for populations of both humans and wildlife. Table 5-41 summarizes the suitability of various grasses and legumes for revegetation purposes. Native species of trees and shrubs, particularly those with a shallow root system, should generally be specified.

Local landscaping contractors should be hired to perform revegetation work, preferably someone who has experience in growing local varieties of vegetation and who can make recommendations on the suitability of the different varieties.

5.9.4.3 Design and Construction Considerations

The selection of suitable plant species for a given disposal site depends on several site-specific variables. These variables include cover soil characteristics (grain size, organic content, nutrient and pH levels, and water content), local climate, and site hydrology (slope steepness and drainage characteristics). Individual species must be chosen on the basis of their tolerance to such site-specific stresses as soil acidity and erodibility. Other important considerations include the compatibility of the species with other plants selected to be grown on the site, resistance to insect damage and diseases, and suitability for future land use.

Table 5-41. **Important Characteristics of Grasses and Legumes***

Characteristics	Common Examples
Texture	
Fine	Kentucky blue grass, bentgrass, red fescue
Coarse	Smooth brome grass, reed canary grass, timothy
Growth height	
Short	Kentucky bluegrass, buffalo grass, red fescue
Medium	Redtop, perennial rye grass
Tall	Smooth brome grass, timothy, switch grass
Growth habit	
Bunch	Timothy, big bluestem, sand dropseed, perennial rye grass
Sod former	Quick grass, smooth brome grass, Kentucky bluegrass, switch grass
Reproduction	
Seed	Red and alsike clover, sand dropseed, rye, perennial rye grass, field brome grass
Vegetative	Prairie cord grass, some bent grasses
Seed and vegetative	White clover, crown vetch, quack grass, Kentucky bluegrass, smooth bromegrass
Annual	
Summer	Rabbit clover, oats, soybeans, corn, sorghum
Winter	Rye, hairy vetch, field brome grass
Perennials	
Short-lived	Timothy, perennial rye grass, red and white clover
Long-lived	Bird's-foot trefoil, crown vetch, Kentucky bluegrass, smooth brome grass
Maintenance	
Difficult	Tall fescue, reed canary grass, timothy, alfalfa
Moderate	Kentucky bluegrass, smooth brome grass
Easy	Crown vetch, white clover, bird's-foot trefoil, big bluestem
Shallow-rooted	
Weak	Sand dropseed, crab grass, foxtail, white clover
Strong	Timothy, Kentucky bluegrass
Deep-rooted	
Weak	Many weeds
Strong	Big bluestem, switch grass, alfalfa, reed canary grass

Table 5-41. **(Continued)**

Characteristics	Common Examples
Moisture	
Dry	Sheep fescue, sand dropseed, smooth brome grass
Moderate	Crested wheat grass, red clover
Wet	Reed canary grass, bent grass
Temperature	
Hot	Lehman love grass, four-wing saltbush, rye grass
Moderate	Orchard grass, Kentucky bluegrass, white clover
Cold	Alfalfa, hairy vetch, smooth brome grass, slender wheat grass

* Data from Lutton 1982.

Long-term vegetative stabilization and site reclamation require the proper planting of compatible mixes of grasses, legumes, shrubs, and trees. Short-term revegetation efforts generally require the use of low-cost, quick-growing perennial and self-seeding annual species, usually grasses. In areas where a quick vegetative cover is essential for preventing erosion and pollutant transport, the use of an approved sod could prove beneficial.

The optimum time for seeding depends on local climatic considerations and the individual species. Early fall seeding is recommended for most perennial species in most localities. Spring and early summer are usually the best times for seeding annuals, but they can be planted for quick vegetation whenever soil is damp and warm. In mild climates (e.g., southeastern United States), the growth of both summer and winter grasses will extend the range of erosion resistance for cover soils.

Mulches or chemical stabilizers may be applied to seeded soils to aid in the establishment of vegetative cover. Organic mulches such as straw, hay, wood chips, sawdust, dry bark, bagasse (unprocessed sugar cane fibers), excelsior (fine wood shavings), and manure protect bare seedbed slopes from erosion prior to germination. Also, thin blankets of burlap, fiberglass, and excelsior can be stapled down or applied with asphalt tacks to form protective mulch mats for germinating seedbeds.

5.9.4.4 Costs

Total 1986 cost estimates for revegetation range from $1290 to $8525/acre. Costs for revegetation vary widely depending upon the site conditions. The lowest cost estimate represents a hypothetical site that required hydroseeding (lime, fertilizer, field seed) only. The highest cost estimate represents a proposed restoration of a secondary growth, temperate, deciduous forest that required heavy liming to neutralize the highly acidic soils. Unit costs associated with revegetation are reported in Table 5-42. All costs are reported in 1986 dollars and include contractors' overhead and profit.

Table 5-42. 1986 Unit Costs Associated With Revegetation

Description	Unit Cost ($)	Source*
Hydraulic spreading (hydroseeding), lime, fertilizer, and seed	873/acre	(1)
Mulching, hay	317/acre	(1)
Loam topsoil	6.70/yd^3	(1)
Loam topsoil, removal and stockpiling 6 feet deep on site with a 200-hp bulldozer		
200-ft haul	1.20/yd^3	(2)
500-ft haul	4.56/yd^3	(2)
Hauling loam 2 miles on site	3.94/yd^3	(1)
Spreading loam 2 to 6 inches deep		
Slopes	1.07 to 3.20/yd^3	(1)
Level areas	0.79 to 2.33/yd^3	(1)
Plant-bed preparation (unspecified), 18 inches deep, by machine	5.60/yd^2	(2)
Hydraulic seeding and fertilization of large areas with wood-fiber mulch	0.42/yd^2	(2)
Handspreading of mulch (wood chips) 2 inches deep	1.26/yd^2	(2)
Liming		
Level areas	90/acre	(1)
Slopes	590/acre	(1)
Fertilizing (no insecticides)		
Level areas	460/acre	(1)
Slopes	660/acre	(1)
Seeding		
Level areas	675/acre	(1)
Slopes	873/acre	(1)
Jute mesh, stapled (erosion control)	0.87/yd^2	(2)
Sodding 1 inch deep		
Level areas	2.93/yd^2	(2)
Slopes	3.37/yd^2	(2)
Maintenance		
Grass mowing		
Slopes	93.20/acre	(1)
Level areas	38.90/acre	(1)
Refertilization	249/acre	(1)
Weeding/pruning shrubs	2000/acre	(1)
Onsite planting		
Trees		
Evergreens	30 to 36 inches, 115 ea.	(1)
	36 to 42 inches, 117 ea.	(1)
	42 to 48 inches, 165 ea.	(1)
	4 to 5 ft, 208 ea.	(1)
	5 to 6 ft, 265 ea.	(1)
Black pines	2.5 to 3 ft, 28 ea.	(2)
Yews	2 to 2.5 ft, 38 ea.	(2)
Junipers	4 to 5 ft, 50 ea.	(2)
Shade trees (balled and burlapped)		

Table 5-42. **(Continued)**

Description	Unit Cost ($)	Source*
Shade trees (balled and burlapped)		
	6 to 8 ft, 79 ea.	(1)
	8 to 10 ft, 111 ea.	(1)
	1.5- to 2.5-in. diameter, 284 ea.	(1)
	2.5- to 4.0-in. diameter, 462 ea.	(1)
Birch	6 to 8 ft, 99 ea.	(2)
Oak	8 to 10 ft, 500 ea.	(2)
Shrubs (balled and burlapped)		
	2 to 3 ft, 60 ea.	(1)
	3 to 4 ft, 90 ea.	(1)
	4 to 5 ft, 110 ea.	(1)
Honeysuckle shrub	3 to 4 ft , 20 ea.	(2)

* Data from (1) McMahon 1984; (2) Means 1984a.

5.10 Restoration of Contaminated Water Supplies and Utility/Sewer Lines (EPA 1985a)

Contaminants from leaking USTs can enter public water systems through a wide variety of pathways and thus contaminate these systems as well as the water in them. Once contaminated, a water system can become a secondary source of contamination to which system users can be exposed over long periods of time.

Sanitary and storm sewers can become contaminated by infiltration of the leaking fluid or contaminated ground water through cracks, ruptures, or poorly sealed joints in piping and by direct discharges into the system. Potable water supply mains also can become contaminated by contact with contaminated water that may inadvertently flow through them, or by infiltration of the leaking fluid or contaminated ground water. Water mains are less susceptible to the infiltration of contaminants, however, because they are generally full-flowing, pressurized systems. The potential public health consequences of the contamination of municipal mains carrying potable water supplies to commercial and residential consumers are obviously much greater than the consequences of contaminated sewage flowing to a treatment plant or runoff draining into surface waters.

5.10.1 Alternative Central Water Supplies

5.10.1.1 General Description

Unless the discovered leak in an underground storage system is a catastrophic one that grossly affects a municipality's central water supply system, an alternative central water supply may not be needed. Nevertheless, some general discussion of the subject is in order. Providing alternative central water supplies or sources of water that serve many users through central distribution systems generally involves one or more of the following approaches:

- Purchase of water from another supply
- Provision of a new surface water intake(s)
- Provision of a new ground-water well(s)

5.10.1.2 Application/Availability

The contaminated water supply may be abandoned, or it may be blended with the new supply to achieve acceptable water quality by dilution. Combinations of the possible approaches may be applied either concurrently (multiple replacement supplies) or consecutively (emergency water purchased from a neighboring supply unit, followed by new wells or intakes).

Purchase of treated water from another supply requires a cross-connection(s) between the systems. Many neighboring public water departments, authorities, and companies maintain networks of interconnections that allow ready flow between systems for emergencies such as droughts, fires, line breakage, or malfunction of treatment facilities. Where cross-connections do not exist, water transmission lines can be installed.

Provision of a new surface water intake may be feasible where a groundwater source is to be replaced or where a replacement surface water intake would hydraulically isolate the water supply system from contaminated surface water.

Provision of new ground-water wells is often feasible where the extent of aquifer contamination is relatively confined and would not be expected to be drawn to the area of influence of the new wells, or where other (usually deeper) aquifers can be tapped as a replacement water supply.

5.10.1.3 Design and Construction Considerations

Surface water is drawn from rivers, lakes, and reservoirs through submerged intake pipes, or through fairly elaborate tower-like structures that rise above the water surface. In the design and operation of intakes, it is important that the water drawn be as clean, palatable, and safe as the source of supply can provide. River intakes are constructed well upstream from points of discharge of sewage and industrial wastes. The selected location should take advantage of deep water, a stable bottom, and favorable water quality and should be protected against floods, debris, ice, and river traffic. Small streams may be dammed up by diversion or intake dams to keep intake pipes submerged and preclude hydraulically wasteful air entrainment. In the siting of lake intakes, consideration must be given to sources of pollution, prevailing winds, surface and subsurface currents, and shipping lanes. Shifting the depth of draft makes it possible to collect clean bottom water when the wind is offshore, and conversely, to collect clean surface water when the wind is onshore. Reservoir intakes resemble lake intakes, but they generally lie closer to shore in the deepest part of the reservoir.

The feasibility of providing new surface-water intakes depends on the following numerous case-specific requirements and conditions:

- Proximity of the point of intake to the water supply system.
- Peak demand flow versus historic and predicted low flow in the water body.
- Downstream environmental, recreational, and commercial effects of reduced flow.
- Quality of the surface water and corresponding treatment requirements.

Section 5.4 addressed the design and construction considerations for ground-water wells.

5.10.1.4 Costs

Costs for an alternate central water supply vary widely depending on the population to be served, ground-water or surface-water source, treatment requirements, and accessibility to an existing alternate water supply. Ground-water well installation costs were addressed in Section 5.4.

5.10.2 Alternative Point-of-Use Water Supplies

5.10.2.1 General Description

Central water supplies that are contaminated at the source or while flowing through pipelines can be replaced permanently or temporarily with an independent supply at each point of usage. Such supplies could include one or a combination of the following: bottled and bulk water, point-of-use wells, and collection of rainwater.

Bottled water and bulk water are commonly used as temporary water supplies on an emergency basis until arrangements can be made for a more permanent water supply. Bottled water is widely available in small quantities from common retail outlets (grocery and drug stores) and in large quantities from commercial distributors. Larger bottles (e.g., five-gallon "water cooler" bottles) require dispensers for convenience purposes. Their full weight (approximately 50 pounds) may present handling and changeover problems for some users.

Point-of-use wells, or individual wells for each user establishment, may offer a permanent alternative to a contaminated central supply, provided the available ground water is and can be expected to remain clean.

Rainwater is rarely an immediate source of municipal water supplies, but it could be used to replace a contaminated water supply. The use of rainwater is generally confined to farms and towns in semiarid regions where no satisfactory ground water or surface-water supplies exist. For individual users, rainwater running off the roof is led through gutters and downspouts to a cistern situated on or below the ground. For municipal service, roof runoff may be combined with water collected from sheds or catches on the surface of ground that is either naturally impervious or rendered so by grouting, cementing, paving, or similar means.

5.10.2.2 Application/Availability

Bulk water can be provided in portable tanks (trailers or tank trucks) by commercial, clean-water contractors and by public emergency service organizations (e.g., Army National Guard). Tanks that are normally used for other purposes, such as milk tank trucks, also have been used. The tanks are typically made available to home owners at temporary, centrally located, distribution points, where small containers can be filled for home use. Whole tanks can be made available to commercial and institutional establishments.

New wells can be installed as long as they will be pumping from an uncontaminated aquifer. The economics of installing a well should be compared with those for other possible solutions for providing potable water.

The gross yield of rainwater supplies is proportional to the receiving or drainage area and the amount of precipitation. Because of the relatively small catchment area available, roof drainage cannot be expected to yield an abundant supply of water, and a close analysis of storm rainfalls and seasonal variations in precipitation must be made if catchment areas, standby tanks, filters, and cisterns are to be proportioned and developed properly.

Bottled water is probably the most readily available solution for temporary alternate water supply, as it can be purchased from local distributors, groceries, convenient stores, and drug stores.

5.10.2.3 Design and Construction Considerations

Schemes for providing bulk water, an alternate central supply, a new surface-water source, new wells, or rainwater collection will be highly site-specific. Local expertise and contractors should be called upon to help devise the total solution; obviously, the local water company should be included in any planning and implementation programs.

For bottled water supply, price, quantity, and delivery are the main considerations. User requirements will need to be ascertained, and a regular delivery schedule should be established and maintained. Logistics of delivery should be left to the supplier (e.g., where to leave the boxes of bottles if there isn't anyone home).

5.10.2.4 Costs

Bottled water costs range from 50¢ to $1 per gallon delivered in quantities. Bulk water costs will depend on the mode of delivery, availability of supply, and other local factors.

The cost of a new well will depend greatly on local conditions, i.e., depth to ground water, availability of ground water, etc. The cost of a 4-inch, 5-gal/min well, 200-feet deep with PVC casing, submersible pump, tank, distribution piping, and installation would be approximately $11,500; annual operating and maintenance costs would run about $360.

Costs for a rainwater system are very site-specific. They depend on the collection and storage system required and piping/pumping required to supply the user.

5.10.3 Treatment of Central Water Supplies

5.10.3.1 General Description

Central water supplies that are contaminated at the source can be treated at central treatment systems to upgrade them to an acceptable quality level. In small communities that pump ground water directly to distribution systems without treatment, providing central treatment may necessitate the installation of new facilities. In large communities that already treat surface water before distribution, upgrading of existing treatment with the installation of polishing units may be necessary.

5.10.3.2 Application/Availability

Available water treatment methods include physical, chemical, and biological technologies, and combinations of these methods may be required for the removal of some contaminants.

Many of the technologies described in subsection 5.7 for ground-water treatment also apply to treatment of contaminated water supplies. In general, however, those technologies that are normally associated with "polishing" (i.e., removal of low concentrations of contaminants), such as activated carbon, ion exchange, and reverse osmosis, are most applicable to treatment of public water supplies.

5.10.3.3 Design and Construction Consideration

Design and construction considerations for the treatment of ground-water supplies were addressed in subsection 5.7.

5.10.3.4 Costs

Costs were provided in subsection 5.7.

5.10.4 Treatment of Point-of-Use Water Supplies

5.10.4.1 General Description

Modern technology has produced a new point-of-use treatment device for contaminated water systems, and a variety of these devices is available on the market today. The following configurations are typical:

- Line-bypass device. The treatment unit is connected to the water line by saddle valve, and treated water is dispensed through a separate faucet that is usually mounted on the kitchen sink. Models are also available for residential icemakers.
- Faucet-mounted device. This unit is mounted on the kitchen or lavatory faucet and treats all the water that flows from that faucet.
- Whole-house unit. This large unit is installed in the main waterline to treat all the water used in a household or business establishment.

These units should be considered as alternatives to supplying bottled water to replace contaminated water systems. Although these treatment devices may be more costly initially, an economic breakeven or savings could result, depending on the length of time the alternative water source is required.

5.10.4.2 Application/Availability

The point-of-use water treatment devices available on the market today, which use activated carbon as the treatment media, are probably the most appropriate for converting water contaminated by a leaking UST into potable water. These are readily available from well-known suppliers (e.g., Sears, Culligan, Water Pic), as are the needed replacement carbon cartridges.

5.10.4.3 Design and Construction Considerations

Several items should be considered in the selection of a point-of-use device. These include being sure the unit is appropriate for the contaminant(s) of concern, that it has the appropriate hydraulic capacity for the application, and that criteria and schedules for maintaining the units are supplied. This information is generally available from the manufacturer or supplier.

The most preferred style of treatment cartridge is one that uses activated carbon in solid block or granular (not powder) form. Also, the cartridge configuration should be such that water flows through the whole cartridge and cannot bypass any section of it.

5.10.4.4 Costs

Bypass-type point-of-use treatment devices with activated carbon elements can be purchased at prices ranging from $70 to $400 each. Installation by a plumber will cost another $50 to $100 or more, depending on the complexity of the installation.

Whole-house units will cost upwards from $1000 installed, depending on the size required and the complexity of the installation.

5.10.5 Replacement of Water and Sewer Lines

5.10.5.1 General Description

Replacement of water and sewer pipelines that are contaminated by contact with hazardous substances is seldom more cost-effective than rehabilitation, but it often is the only practical alternative. Replacement involves excavation of trenches, laying of new lines with uncontaminated pipe materials, laying new connections and/or tying in connections, and the associated backfilling and surface restoration. Contaminated pipelines may either be abandoned in-place or be removed during trench excavation. Construction of water and sewer lines is common in land development projects, and the associated methods, materials, and equipment are well established.

5.10.5.2 Application/Availability

Pipeline replacement is applicable in virtually all cases of pipeline contamination. The primary disadvantage of pipeline replacement is its high cost. Analyses to determine the cost-effectiveness of replacement must include all costs associated with the replacement; typically, these include pavement removal and replacement, excavation, possible substitution of select backfill to replace poor quality existing or contaminated material, dewatering and shoring, pipe materials, and traffic control. Higher costs can result from interference with other underground utilities. Narrow easements or limited space for construction also must be considered, as well as the need for temporary rerouting of the flow to maintain service. Depending on the service life assumed for other rehabilitation methods, these high capital costs may be offset somewhat by the longer service life a new line provides.

5.10.5.3 Design and Construction Considerations

In general, new pipeline systems will be much like the systems they replace (size, material, grade, location, capacity, etc.). The considerations that govern the design of new systems will apply, but not control. Logistics and the presence of fixed constraints will dictate how the replacement system is designed. The need for replacement, however, may provide an "opportunity" to upgrade the systems in terms of capacity, improved materials and methods, location, and/or direction of flow. Also, some consideration can be given to the criteria for the design of new systems.

Various conventional and unconventional methods are available for constructing water and sewer lines. The most common method, open-trench excavation, often requires lateral bracing of trench walls in deep cuts or noncohesive soils. Other construction methods include augering or boring, jacking, and tunneling. Their use applies in limited situations only, however.

5.10.5.4 Costs

Representative costs for replacement of water and sewer lines are shown in Table 5-43.

Table 5-43. 1986 Unit Costs for Replacement of Water and Sewer Lines*

Item	Cost Per Unit ($)
Sewer pipe, material and installation, in-place	
8-inch diameter	6 to 10/lin. ft.
18-inch diameter	13 to 32/lin. ft.
36-inch diameter	34 to 125/lin. ft.
Water pipe, material and installation, in-place	
2-inch diameter	3 to 7/lin. ft.
4-inch diameter	5 to 11/lin. ft.
12-inch diameter	16 to 28/lin. ft.
Pipe bedding material	
14 to 26/yd^3	
Trench excavation, backfill, and compaction	
Water lines	1 to 3/lin. ft.
Sewer lines	6 to 10/yd^3

* Data from Means 1984a.

5.10.6 Cleaning/Restoration of Water and Sewer Lines

5.10.6.1 General Description

Available techniques for inspecting and cleaning sewerlines generally also apply to waterlines. Waterlines are normally smaller in diameter than sewerlines, however, and size is often a limiting factor in the applicability of inspection and cleaning technologies. Inspection techniques include smoke testing, dye-water flooding, first-hand visual observation, and closed-circuit television visual observation.

Waterlines and sewerlines that have come in contact with contaminated substances or have been infiltrated by contaminated water can be lined or sealed in place with chemically inert material. Available methods for sealing out contaminants include:

- Insertion of new pipe inside of existing pipe (sliplining)
- In-place forming of new pipe inside of existing pipe
- Point repairs of leaks and other defects

Sliplining involves sliding a flexible liner pipe of slightly smaller diameter into an existing circular pipeline and then reconnecting the service connections to the new liner. Polyethylene is the most common material used for sliplining pipelines.

A patented system called "inversion lining" involves the use of a flexible lining material that is thermally hardened. Access to the pipeline can be made through manholes or excavations. After the lining system has been installed and cured, a special cutting device is used to reopen service connections (with the help of a closed-circuit television camera).

Because inversion lining can be accomplished relatively quickly and without excavation, this method is particularly well suited for repairing pipelines located under existing structures or large trees. It also is particularly useful for repairing pipelines located under busy streets or highways, where traffic disruption must be minimized. Inversion lining is relatively new in the United States, and its cost-competitiveness has not yet been fully established. It is available only through a limited number of licensed contractors.

5.10.6.2 Application/Availability

Cleaning of waterlines and sewerlines removes deposits and debris from the pipelines. Its purpose is to improve flow conditions and capacity, to allow visual inspections, and to provide clean surfaces for placement of repair materials.

Available sewer-cleaning techniques include mechanical scouring, hydraulic scouring and flushing, bucket dredging, suction cleaning with pumps or vacuum, chemical absorption, or a combination of these methods. Access to sewerlines for interior cleaning and repair is usually through manholes. Basin inlets and service connections provide additional points of access. Service and fire hydrant connections afford access to municipal waterlines.

Inversion lining, which involves the use of water to cure the resins, is generally used in pipelines with diameters less than 57 inches and manhole-to-manhole segments less than 1000 feet long. Larger-diameter pipelines (up to 108 inches) have been lined by inversion techniques in which air is used.

Chemical grouting is commonly used to seal leaking joints in structurally sound sewer pipes. Small holes and radial cracks also can be sealed by chemical grouting.

Sliplining is used to rehabilitate extensively cracked pipelines, especially those lain in unstable soil conditions. This technique is also used to rehabilitate pipe installed in a corrosive environment and in areas where sewer pipes have massive, destructive, root-intrusion problems. The flexible liner pipes have the advantage of being able to accommodate a normal amount of future settlement or moderate horizontal or vertical deflection.

5.10.6.3 Design and Construction Considerations

Design of waterline and sewerline rehabilitation efforts consists primarily of planning for the logistics of implementation. Sections of pipeline to be rehabilitated are identified by television or other inspection methods. Critical points of operation are selected, such as access manholes, base of operation, and material storage. Methods of managing disruption of services (water or sewer) and of surface activities such as traffic are also planned. Affected parties are notified in advance of the planned work.

Before a liner pipe is installed, the existing pipeline should be inspected by closed-circuit television to identify all obstructions (e.g., displaced joints, crushed pipe, and protruding service laterals) and to locate service connections. The existing pipe is thoroughly cleaned immediately, before sliplining begins.

HDPE sliplining is pulled through existing pipelines by a cable fed through the section to be lined. The cable and pipe are advanced by a winch and pully assembly. An approach trench is excavated at the insertion end of the existing pipe section to allow a gradual transition from the ground surface, where sections of HDPE pipe are heat-fused to form a continuous pipe to an opened section of pipe. Several thousand feet of waterline or sewerline can be sliplined in a single setup of such an operation. Fiberglass-reinforced pipe can be sliplined in a similar manner, but a combination of pushing and pulling of the pipe may be required.

In-place forming of new pipe inside of existing pipe is accomplished with portland cement grout and mortar, chemical grouts, and synthetic resins. Chemical grouts can be used to seal fractures and leaking joints to waterproof points of infiltration/exfiltration. Grout materials used for this application include acrylamide, acrylate, urethane, and polyurethane.

Grouting combined with sealing rings requires the use of a small control panel, chemical and water pumps, and various other accessories, depending on the type of sealing grout being used. A worker must enter the line, manually place the ring over the joint, and inflate the ring to isolate the joint. Sealing grout is pumped into the small void between the pipe wall and the face of the ring with a hand-held probe. As the pressure in the void increases, the grout solution is forced into the joint and surrounding soil. A catalyst solution is injected, and the grout cures, thereby sealing the joint from infiltration.

5.10.6.4 Costs

Waterlines can be inspected and cleaned by a variety of methods and at varying costs. Television inspection and light high-pressure water cleaning (the minimum required in preparation for repairing or lining pipelines) typically cost $100 to $155 per hour, or $0.40 to $0.60 per linear foot to cover 2000 feet of pipe per 8-hour day and $0.80 to $1.25 per linear foot to cover 1000 feet of pipe per day. Costs of other inspection and cleaning methods are highly variable and depend on the type of pipeline and nature of the material being removed.

Costs of sliplining waterlines and sewerlines vary with the diameter and depth of the pipeline. Costs for relatively small-diameter (less than 15-inch) HDPE sliplining projects range from $20 to $30 per linear foot. Larger-diameter sliplining projects are seldom undertaken and must be costed on a project-specific basis.

Inversion lining costs are normally given on a per-linear-foot basis for initial television inspection, cleaning, bypass pumping, and post-construction television inspection combined. The following are representative unit costs for typical inversion lining of sewerlines:

Diameter (inches)	Cost ($/linear ft)
8	45 to 51
10	47 to 53
12	49 to 55

Reconnection of laterals typically costs $100 to $260 each, depending on logistics and the number of laterals in a given project.

Grout repairs to sewer pipelines are generally accomplished by pumping grout into a joint until soil voids are filled, as determined by back pressure. A wide range of grout volumes can be pumped into a joint, and sewer grouting work is typically conducted on a per-hour basis for manpower and equipment ($100 to $155 per hour) and on a per-gallon basis for grout ($5 to $10 per gallon for chemical grout).

Section 6
Reference Matrix for Case Histories

6.1 Purpose of Case Histories

Real-world experience in the remediation of releases from underground storage tanks is poorly documented. An extensive review of the literature revealed fewer than 40 reported cases of leaking underground tanks/piping and attempts to implement corrective-action programs. Given the broad population of underground tanks and the high probability of tank failure, this is a small number indeed. Nevertheless, the cases reported in the literature provide a basis on which to evaluate the applicability of more conventional corrective-action technologies to subsurface releases of petroleum and chemical products under a variety of site conditions. The purpose of including the case histories in this report is to provide the reader with real-world applications of various technologies along with information on performance and costs.

Ten case histories relating UST corrective action experience are presented in the appendix. Each of these case histories provides the following information:

- Background - A brief description of the circumstances leading to the discovery of the leaking underground tank/pipeline.
- Site description - A detailed description of the site's geologic/hydrogeologic characteristics, including depth to water-table and proximity to any drinking water supply wells (where available).
- Nature and extent of contamination - Estimates of the volume of product (petroleum, chemical) released and the vertical and horizontal dimensions of the plume.
- Corrective actions - A summary of the initial and remedial measures to control the release, contain the plume, and clean up contaminated soils, ground water, and surface water.
- Project evaluation - An assessment of the effectiveness of the corrective actions in meeting the cleanup objectives in a timely manner.
- Costs - A summary of the total capital and annual operating expenditures (where available) to implement the corrective-action program.

It is hoped that this information will be of value to site owners/operators, cleanup contractors, and regulatory personnel contemplating alternative corrective-action responses at other UST locations.

6.2 Case History Matrix

The matrix presented in Figure 6-1 summarizes the salient aspects of each of the case histories contained in the appendix. As shown in the matrix, the case histories encompass a broad range of facility types, hydrogeologic settings, and types and quantities of product(s) released. Sixteen of the corrective action technologies profiled in Section 5 are represented in the case histories.

The matrix leads to two conclusions: 1) a successful corrective-action program requires implementation of a combination of response technologies, and 2) ground-water extraction will be an integral part of nearly every corrective-action program. These points should be considered in the response to releases from underground tanks.

Figure 6-1. Case history matrix.

	Environmental Monitoring				Corrective Action Technologies															
Case History	Soil	Ground Water	Surface Water	Air	Tank/Piping Removal	Soil Excavation	Free Product Recovery, Dual-Pump System	Free Product Recovery Single-Pump System	Extraction Well	Injection Well	Trench/Subsurface Drain	Infiltration Gallery	Slurry Wall	Soil Flushing	Biostimulation	Air Stripping	Carbon Adsorption	Biological Treatment	Granular Media Filtration	Density Separation
A. Gasoline Pipeline, Glendale, CA 100,000 to 250,000 gal gasoline released; ground-water aquifer, alluvial deposit; 70 ft to water table; 400 ft from drinking water supply		●						●	●		●									●
B. Gasoline Pipeline, Ambler, PA 100,000 gal gasoline released; highly fractured dolomite; 30 to 100 ft to water table; 300 ft from drinking water supply		●			●			●	●	●					●					
C. Retail Gasoline Station Genesee County, MI Undetermined amount of gasoline released; ground-water aquifer, fine glacial sand; 15 to 20 ft to water table		●					●		●											
D. Retail Gasoline Station Montgomery County, PA Undetermined amount of gasoline released; ground-water aquifer, fractured shale siltstone, 15 to 20 ft to water table; 200 ft from drinking water supply				●	●			●			●			●	●					
E. U.S. Coast Guard Air Station Traverse City, MI 200 + gal of jet fuel and aviation fuel released (benzene and toluene); 1200 ft from drinking water supply	●	●	●		●	●			●									●		

Figure 6-1. (Continued)

	Environmental Monitoring				Corrective Action Technologies															
	Soil	Ground Water	Surface Water	Air	Tank/Piping Removal	Soil Excavation	Free Product Recovery, Dual-Pump System	Free Product Recovery Single-Pump System	Extraction Well	Injection Well	Trench/Subsurface Drain	Infiltration Gallery	Slurry Wall	Soil Flushing	Biostimulation	Air Stripping	Carbon Adsorption	Biological Treatment	Granular Media Filtration	Density Separation
F. Bulk Fuel Storage and Distribution Center 200,000 gal of fuel oil released; ground-water aquifer, fractured dolomite; 50 ft to water table		●			●		●		●			●								
G. Midwestern Laboratory Facility 1000 to 1500 gal of fuel oil and solvents released; ground-water aquifer, glacial till	●	●					●		●	●				●	●		●			
H. Chemical Pipeline Undetermined amount of methylene chloride released; 100 ft to water table		●				●		●	●	●						●		●	●	●
I. Biocraft Laboratories, Waldwick, NJ 33,000 gal of methylene chloride, acetone, m-butyl alcohol, and dimethyl aniline released; ground-water aquifer, glacial till and fractured shale; 0 to 9 ft to water table; 1000 ft from drinking water supply		●	●						●		●	●						●		
J. Fairchild Camera & Instrument Corp., South San Jose, CA 43,000 gal of 1,1,1-trichloroethane, xylene, acetone, and isopropyl alcohol released; ground-water aquifer, alluvial deposits; 10 to 40 ft to water table; 2000 ft from drinking water supply	●	●		●	●	●			●	●			●	●		●	●			

References

American Petroleum Institute. 1979. Installation of Underground Petroleum Storage Systems. Publication 1615. Washington, D.C.

American Petroleum Institute. 1980. Underground Spill Cleanup Manual. Publication 1628. Washington, D.C.

American Petroleum Institute. 1981. Recommended Practice for Abandonment or Removal of Used Underground Service Station Tanks. Publication 1604. Washington, D.C.

Bureau of Reclamation. 1978. Drainage Manual. Denver, Colorado.

Bureau of National Affairs. 1985. Cities Must Begin Registering Tanks to Meet May Deadline, EPA Official Says. Environmental Reporter, 16(35): 1664-1665.

Camp, Dresser, and McKee, Inc. 1986. Fate and Transport of Substances Leaking From Underground Storage Tanks. Volume 1, Technical Report. Interim report prepared for the U.S. Environmental Protection Agency under Contract No. 68-01-6939.

Canter, L. W., and R. C. Knox. 1985. Ground Water Pollution Control. Lewis Publishers, Inc., Chelsea, Michigan.

Chemical Separations Corp. Undated. Ion Exchange Systems (a sales brochure) Oak Ridge, TN.

Cheremisinoff, P. N., et al. 1986. Special Report: Underground Storage Tank Control. Pollution Engineering, 18(2):22-29.

CONCAWE. 1979. Protection of Groundwater From Oil Pollution. Report No. 3/79. The Hague, Netherlands.

Conway, R. A., and R. D. Ross. 1980. Handbook of Industrial Waste Disposal. Van Nostrand Reinhold Co., New York.

Cope, F. W., G. Karpinski, and R. L. Steiner. 1984. Use of Liners for Containment at Hazardous Waste Landfills. Pollution Engineering, 14(3):22-32.

Cullinane, M. J., and L. W. Jones. 1985. Technical Handbook for Stabilization/Solidification of Hazardous Waste. Prepared for U.S. Environmental Protection Agency, Hazardous Waste Engineering Research Laboratory, Cincinnati.

Culp, R. L., Wesmer, and G. L. Culp. 1978. Handbook of Advanced Wastewater Pretreatment. Van Nostrand Reinhold Environmental Engineering Series, New York.

De Renzo, D. (ed.) 1978. Unit Operation for Treatment of Hazardous Wastes. Noyes Data Corporation, Park Ridge, New Jersey.

Driscoll, F. G. 1986. Groundwater and Wells. 2nd Ed. Johnson Division, UOP, St. Paul, MN.

Ehrenfeld, J. R., and J. M. Bass. 1983. Handbook for Evaluating Remedial Action Technology Plans. EPA-600/2-83-076.

Environmental Law Institute. 1985. Compendium of Cost of Remedial Technologies at Hazardous Waste Sites. A Report to the Office of Emergency and Remedial Response, U.S. Environmental Protection Agency.

FMC Corporation. 1985. An Introduction to FMC's Enhanced Bioreclamation. FMC Aquifer Remediation Systems, Princeton, NJ.

Ghassemi, M., K. Yu, and S. Quinlivan. 1981. Feasibility of Commercialized Water Treatment Techniques for Concentrated Waste Spills. Prepared for the U.S. Environmental Protection Agency, Municipal Research Laboratory, Cincinnati, Ohio.

Giddings, T. 1982. The Utilization of a Groundwater Dam for Leachate Containment at a Landfill Site. In: Proceedings of Aquifer Restoration and Groundwater Rehabilitation, 2nd National Symposium on Aquifer Restoration and Groundwater Monitoring, Columbus, Ohio, May 26-28, 1982. pp. 23-29.

Gooding, C. H. 1985. Reverse Osmosis and Ultrafiltration. Chemical Engineering, January 5, 1985, pp. 56-62.

Hansen, S. P., R. Gumerman, and R. Culp. 1979. Estimating Water Treatment Costs. Volume 3: Cost Curves Applicable to 2500 gpd to 1 mgd Treatment Plants. EPA-600/2-79-162c. U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Cincinnati, Ohio.

Johnson Division, UOP, Inc. 1975. Groundwater and Wells. A Reference Book for the Water-Well Industry. St. Paul, Minnesota.

JRB Associates. 1985. Leachate Plume Management. EPA No. 540/285-004. Prepared for the U.S. Environmental Protection Agency, Cincinnati, Ohio.

Kiang, Y., and A. R. Metry. 1982. Hazardous Waste Processing Technology. Ann Arbor Science Publishers, Inc., Ann Arbor, MI.

Knapp, Inc. 1982. Polly-Pig. Technical Bulletin B5/82/5M. Knapp, Inc., Houston, TX.

Knox, R. C., et al. 1984. State-of-the-Art Aquifer Restoration. Volumes 1 and 2. EPA/600-2-84-182a and b.

Lundy, D. A., and Mahan, J. S. 1982. Conceptual Designs and Cost Sensitivities of Fluid Recovery Systems for Containment of Plumes of Contaminated Groundwater. In: Proceedings of National Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, D.C., November 29-December 1, 1982. pp. 136-140.

Lutton, R. 1982. Evaluating Cover Systems for Solid and Hazardous Waste. SW-867. U.S. Army Engineers Waterways Experiment Station. Prepared for U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Cincinnati, Ohio.

McMahon, L. A. 1984. 1985 Dodge Guide to Public Works and Heavy Construction Costs. Annual Edition No. 17. McGraw-Hill Information Systems Company, Princeton, NJ.

Robert Snow Means Company, Inc. 1984a. Means Building Construction Cost Data 1985. 39th ed. R. S. Godfrey, ed. Kingston, MA.

Robert Snow Means Company, Inc. 1984b. Means Site Work Cost Data 1985. 4th ed. R. S. Godfrey, ed. Kingston, MA.

Michelsen, D. L., D. A. Wallis, and S. R. Lavinder. 1985. In Situ Biodegradation of Dispersed Organics Using a Microdispersion of Air in Water. In: Proceedings of the Sixth National Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, D.C., November 4-6, 1985. Hazardous Materials Control Research Institute, Silver Spring, Maryland.

Montgomery, R. E., D. P. Remeta, and M. Gruenfeld. 1985. Rapid On-Site Methods of Chemical Analysis. In: Contaminated Land. Michael A. Smith, ed. Plenum Publishing Corporation, New York.

National Fire Protection Association. 1981. Flammable and Combustible Liquids Code. NFPA 30. Quincy, Massachusetts.

National Fire Protection Association. 1982. Recommended Practice for the Control of Flammable and Combustible Liquids and Gases in Manholes, Sewers, and Similar Underground Structures. NFPA 328-1982. Quincy, Massachusetts.

New York State Department of Environmental Conservation. Undated. Recommended Practices for Underground Storage of Petroleum. Albany, New York.

Niaki, S., and J. A. Broscious. 1986. Underground Tank Leak Detection Methods: A State-of-the-Art Review. EPA-600/2-86-001.

Oil Recovery Systems, Inc. Undated. Floating-filter Recovery system. Promotional Literature. Novi, MI.

Powers, J. P. 1981. Construction Dewatering. A Guide to Theory and Practice. John Wiley & Sons, New York.

Sammons, J. H., and J. M. Armstrong. 1986. Use of Low Flow Interdiction Wells to Control Hydrocarbon Plumes in Groundwater. In: Proceedings of the National Conference on Hazardous Wastes and Hazardous Materials, Atlanta, Georgia, March 4-6, 1986. Hazardous Materials Control Research Institute, Silver Spring, Maryland.

Schwab, G. O., et al. 1981. Soil and Water Conservation Engineering. John Willey and Sons, New York.

Shepherd, W. D. No date. Practical Geohydrological Aspects of Groundwater Contamination. Department of Environmental Affairs, Shell Oil Company, Houston, Texas.

Sims, R. C., et al. 1985. Review of In-Place Treatment Techniques for Contaminated Surface Soils. Volumes 1 and 2. EPA-540/2-84-003a and b.

Spooner, P. A., et al. 1984a. Slurry Trench Construction for Pollution Migration Control. EPA-540/2-84-001.

Spooner, P. A., et al. 1984b. Compatibility of Grouts With Hazardous Wastes. EPA-600/2-84-015. Prepared by JRB Associates for the U.S. Environmental Protection Agency.

Tusa, W. 1986. Underground Leaks: True Corporate Costs. Pollution Engineering, 18(2):68-81.

Ueguhardt, L. C., et al. 1962. Civil Engineering Handbook. McGraw-Hill, New York.

U.S. Environmental Protection Agency. 1973. Process Design Manual for Activated Carbon Adsorption. EPA 625/1-71-002a.

U.S. Environmental Protection Agency. 1979. Process Design Manual: Sludge Treatment and Disposal. EPA 625/1-79-011. Municipal Environmental Research Laboratory, Cincinnati, Ohio.

U.S. Environmental Protection Agency. 1980. Innovative and Alternative Technology Assessment Manual. EPA-430/9-78-009.

U.S. Environmental Protection Agency. 1982. Design Manual: Dewatering Municipal Wastewater Sludges. EPA-625/1-82-014.

U.S. Environmental Protection Agency. 1984. Case Studies No. 1-23: Remedial Response at Hazardous Waste Sites. EPA-540/2-84-002b.

U.S. Environmental Protection Agency. 1985a. Handbook - Remedial Action at Waste Disposal Sites (Revised). EPA-625/6-85-006.

U.S. Environmental Protection Agency. 1985b. In Situ Flushing and Soils Washing Technologies for Superfund Sites. A Collection of Papers Presented at the RCRA/Superfund Engineering Technology Transfer Symposium by the Hazardous Waste Engineering Research Laboratory, Cincinnati, Ohio.

U.S. Environmental Protection Agency. 1985c. Fact Sheet. Mobile System for Extracting Spilled Hazardous Materials From Soil. Hazardous Waste Engineering Research Laboratory, Releases Control Branch, Edison, New Jersey.

U.S. Environmental Protection Agency. 1985d. Leachate Plume Management. EPA/540/2-85/004.

Vatavuk, W. M., and R. B. Neveril. 1983. Cost of Flares. Chemical Engineering. Vol. 90, No. 4.

Virginia Soil and Water Commission. 1980. Virginia Erosion and Sediment Control Handbook: Standards, Criteria and Guidelines. Richmond, VA.

Wagner, K., and Z. Kosin. 1985. In Situ Treatment. In: Proceedings of the Sixth National Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, D.C., November 4-6, 1985. Hazardous Materials Control Research Institute, Silver Spring, Maryland.

Water Information Center, Inc. 1986. Pennsylvania Makes Assessment of Its LUST Investigations. The Groundwater Newsletter, 14(9):2.

Whittaker, H. 1984. Development of a Mobile Reverse Osmosis Unit for Spill Cleanup. In: Proceedings of Hazardous Material Spills Conference, April 9-12. Government Institutes, Inc., Rockville, Maryland.

Yaniga, P. M. 1984. Hydrocarbon Contamination of Ground Water: Assessment and Abatement. Testimony Presented by Paul M. Yaniga on March 1, 1984, to Hearings of the United States Senate Committee on Environmental and Public Works.

Appendix
Case Histories

A.1 Case History A–Gasoline Pipeline, Glendale, California

A.1.1 Background

On April 15, 1968, gasoline odors were detected at a drinking fountain in Forest Lawn Memorial Park in Glendale, California. By September 12, engineers had traced the source of the odors to Well No. 4 (FL-4). A buried 8-inch steel pipeline, which was used to transport refined gasoline, traversed the area. Several minor leaks (totalling less than 6000 gallons) in this line had been reported (and repaired) since 1964; however, preliminary estimates of the extent of contamination indicated that between 100,000 and 250,000 gallons may have leaked (McFee, Laverty, and Hertel 1972).

A.1.2 Site Description

Forest Lawn Memorial Park is located in a hilly area bordering the somewhat narrow alluvial valley of the Los Angeles River. The upper Los Angeles River area is an important ground-water resource for southern California. The pipeline release occurred on the relatively flat ground-water divide between two major well fields that supply water to the city of Los Angeles (Figure A-1).

Geologic maps and numerous exploratory wells in the Forest Lawn area indicate a clay layer at a depth of about 100 feet below the ground surface. Depth to ground water was approximately 70 feet in the fall of 1968, but had been recorded as shallow as 30 feet and as deep as 100 feet during periods of floods and droughts. Because the water table is nearly flat, horizontal movement of the ground water in the vicinity of the pipeline release was extremely slow (McKee, Laverty, and Hertel 1972).

A.1.3 Nature and Extent of Contamination

Immediate action was taken to determine the extent of contamination, and by August 1969, some 30 observation wells had been drilled. During the course of the drilling, free gasoline was found floating on the water table at thicknesses of 12 to 30 inches. Free gasoline was estimated to cover an area of more than 160,000 square feet (Blevins and Williams 1985).

A.1.4 Corrective Action

When pumping of FL-4 was stopped in September 1968, a considerable depth of free gasoline accumulated on top of the water table. In the first month after pumping ceased, approximately 1000 gallons of gasoline was removed by bailing. Selected observation wells were subsequently equipped with skimmer pumps for recovery of free product. Extracted gasoline/water was treated by gravity separators at three small treatment plants constructed in the Forest Lawn area. Floating gasoline was removed and trucked away; the underlying water was discharged to storm drains or to a lined flood-control channel. About 20,000 gallons of gasoline was recovered in this manner over the next year (McKee, Laverty, and Hertel 1972).

In November 1969, however, free gasoline appeared for the first time in a well 500 feet closer to one of the major supply well fields (Pollock Field) than that which had been detected initially. Pumping from the well field was stopped immediately to minimize drawdown toward the field. Further drilling and testing in the Forest Lawn area helped to contain the plume by creating localized cones of depression.

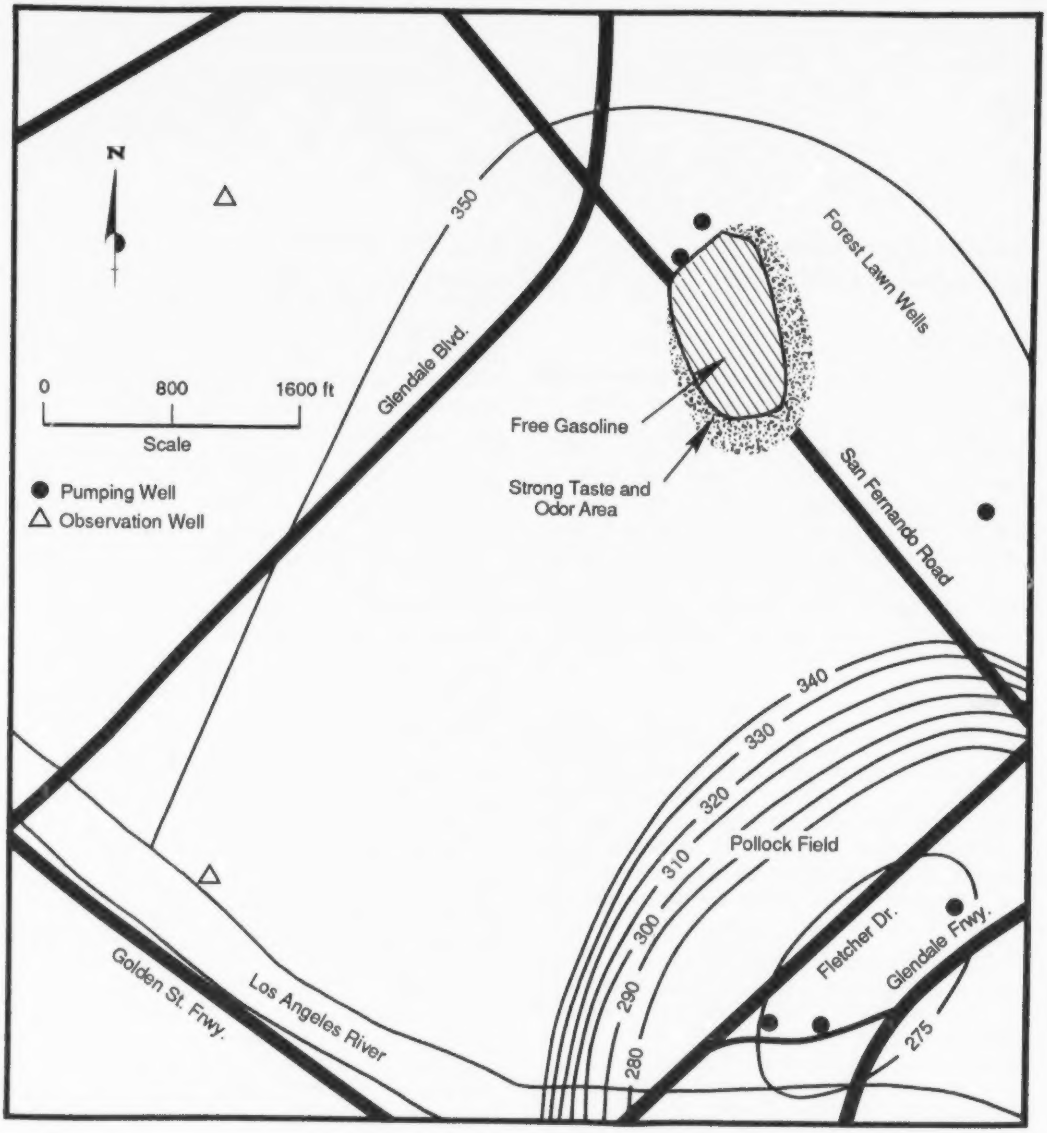
Extraction of ground water and separation of free product continued through August 1971, when free product recovery was essentially complete; however, strong taste and odor problems persisted in many of the supply wells in the Forest Lawn and Pollock Field areas. Biodegradation of the pellicular gasoline by naturally occurring bacteria (*Pseudomonas* and *Arthrobacter*) over the next several years eventually eliminated the bad taste and odors (Blevins and Williams 1985).

A.1.5 Performance Evaluation

From September 1968 through August 1971, about 50,000 gallons of free product was recovered. By mid-1971, the extent of gasoline contamination was limited to a few wells in the immediate vicinity of Forest Lawn (Blevins and Williams 1985).

Ground-water sampling through August 1971 showed gasoline-degrading bacteria to be present at concentrations of 50,000/ml or higher in wells that contained traces of free product; bacteria were found at concentrations of 5,000 to 50,000/ml in wells with

Figure A-1. Site of gasoline pipeline break (Blevins and Williams 1985).


N
0
800
1600 ft
Scale
● Pumping Well
△ Observation Well
350
Glendale Blvd.
Forest Lawn Wells
Free Gasoline
Strong Taste and Odor Area
San Fernando Road
340
330
320
310
300
290
280
275
Pollock Field
Fletcher Dr.
Glendale Frwy.
Golden St. Frwy.
Los Angeles River

taste and odor problems (Blevins and Williams 1985). This correlation between the amount of available hydrocarbons and the concentration of bacteria indicates that natural biodgradation of the pellicular gasoline was occurring.

Since February 1976, measurements by sensitive paste on a weighted tape have shown no trace of free gasoline in any of the wells. No odors have been detected by sniffing since April 1976. Infrared analyses for hydrocarbons performed biweekly from July through September 1976 produced essentially negative results (Blevins and Williams 1985). Because of the lack of any detectable odor or any significant levels of hydrocarbons by analysis, monitoring of the site was terminated on December 31, 1976.

A.1.6 Project Costs

Project costs have not been published.

A.1.7 References

Blevins, M. L., and D. E.Williams. 1985. Management of Gasoline Leaks - A Positive Outlook. In: Innovative Means of Dealing with Potential Sources of Ground Water Contamination; Proceedings of the Seventh National Ground Water Quality Symposium, Las Vegas, Nevada, September 26-28, 1984. EPA-600/9-85-012.

McKee, J. E., F. B. Laverty, and R. M. Hertel. 1972. Gasoline in Ground-water. J. of the Water Pollution Control Federation, 44(2):293-302.

A.2 Case History B—Gasoline Pipeline, Ambler, Pennsylvania

A.2.1 Background

In July 1971, a pipeline break near Ambler, Pennsylvania, spilled an estimated 100,000 gallons of high-octane gasoline into the subsurface, which contaminated the Whitemarsh Township water supply.

A.2.2 Site Description

The spill occurred in a valley approximately 500 feet east of a small creek and 300 feet north of a municipal pumping station. The contaminated aquifer is composed of a highly fractured dolomite. Depending on its location relative to the creek, the depth to ground water varies from 30 to 100 feet (FMC 1972).

Natural ground-water flow in the region is toward the creek; however, the natural gradient is reversed when the two municipal wells, which draw 1 million gallons of water per day, are being pumped. Under these conditions, the creek is a source of ground-water recharge.

A.2.3 Nature and Extent of Contamination

Because the two municipal wells were being pumped at the time the spill occurred, the gasoline was largely confined to the area within the radius of influence of the well system. Over the next 8 months, 46 wells were drilled in the area to define the extent of contamination and to act as recovery points (Figure A-2). Details on the extent of contamination were not available.

A.2.4 Corrective Action

Shortly after its discovery, the broken pipeline was drained and replaced. Gasoline floating on the water table was recovered through continued pumping of the municipal wells. The extracted ground water was discharged to a ditch to allow separation of any free product before the water entered a nearby creek.

Physical methods were successful in recovering only about two-thirds of the spilled product during the first year (FMC 1972, Lee and Ward 1984). Much of the remaining product was believed to be trapped in tiny crevices and adsorbed to soil particles. Extraction of the contaminated ground water, which contained 5 ppm dissolved hydrocarbons, and its treatment by conventional means could take up to 100 years for complete elimination of the contaminants and restoration of the subsurface environment (FMC 1972). For this reason, an alternative cleanup technique--biostimulation--was pursued.

The biostimulation program was initiated in 1972. Nitrogen and phosphorus as 30 percent solutions of ammonium sulfate [$(NH_4)_2SO_4$)], disodium phosphate (Na_2HPO_4), and monosodium phosphate (NaH_2PO_4) were introduced through injection wells to provide the natural gasoline-degrading bacteria with the nutrients required for their growth. Dissolved oxygen was supplied by sparging air into wells through diffusers connected to paint-sprayer-type compressors. On the average, 10 aeration systems supplying air at a rate of 2.5 ft^3/min were used. Ground-water flow was controlled by a series of injection and production wells.

A.2.5 Performance Evaluation

The introduction of nutrients led to an average 100-fold increase in the number of gasoline-degrading bacteria in wells within the spill area. The average concentration of bacteria appeared to correspond to the availability of gasoline and averaged 10^7/ml in the center of the spill and 10^4/ml beyond its perimeter. Thirty-two bacterial cultures, principally *Norcardia*, *Pseudomonas*, and *Arthrobacter*, were isolated during the project (FMC 1972).

Nutrient addition was stopped in February 1974. By that time, the levels of gasoline in the production wells had been reduced from 5 ppm to less than 2.5 ppm. Within 6 months, gasoline in these wells was reduced to less than detectable levels (0.5 ppm based on UV analysis) (FMC 1972).

A.2.6 Project Costs

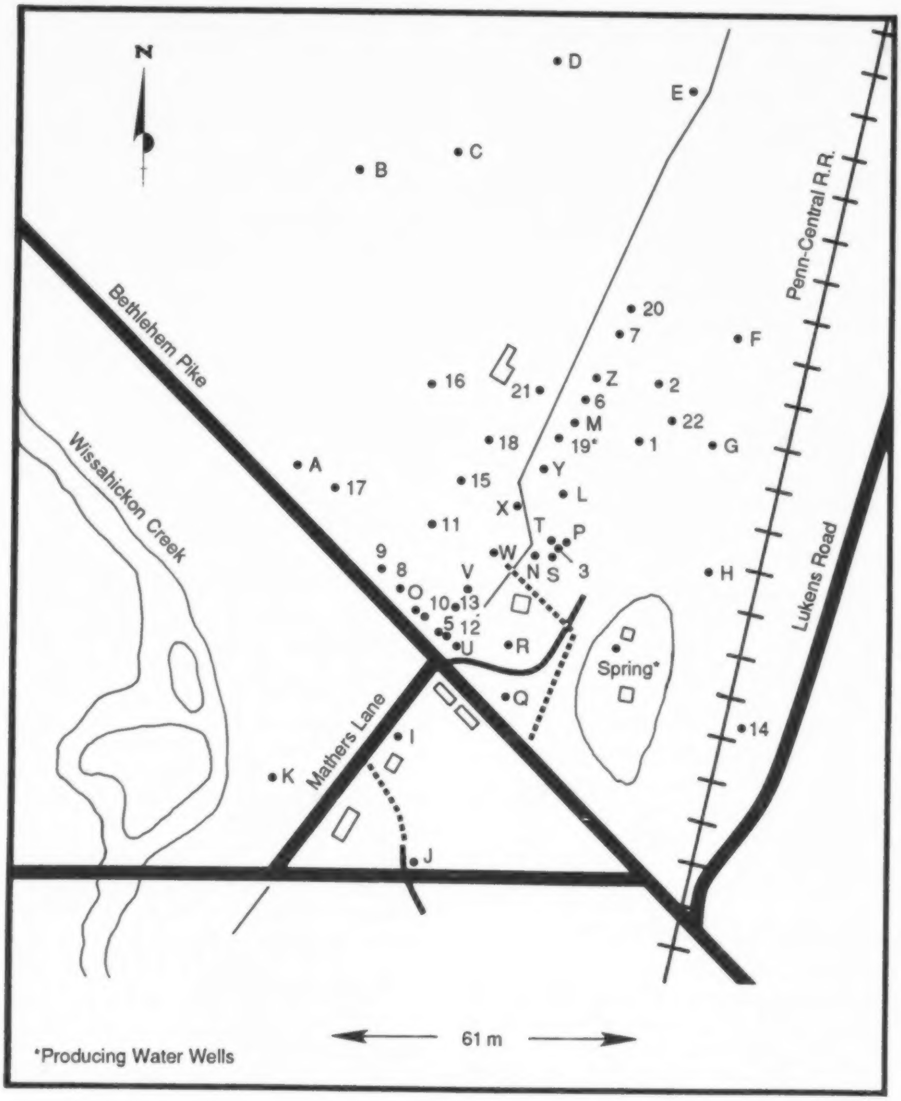
Project costs have not been published.

A.2.7 References

FMC Corporation.1972. Case History - Gasoline Pipeline Leak Promotional Literature. Princeton, NJ.

Jamison, V. W., R. L. Raymond, and J. O. Hudson, Jr. 1975. Biodegradation of High-Octane Gasoline in Groundwater. In: Developments in Industrial Microbiology, Volume 16; Proceedings of the 31st General Meeting of the Society for Industrial Microbiology, Memphis, Tennessee, August 11-16, 1974. American Institute of Biological Sciences, Washington, D.C.

Figure A-2. Location of observation and recovery wells (Jamison, Raymond, and Hudson 1975).


N
D
E
C
B
Penn-Central R.R.
Bethlehem Pike
Wissahickon Creek
20
7
F
16
21
Z
2
6
M
22
18
19*
1
G
A
17
15
Y
L
X
11
T
P
9
W
N
S
3
8
V
H
Lukens Road
O
10
13
5
12
U
R
Spring*
Q
14
Mathers Lane
I
K
J
61 m
*Producing Water Wells

Lee, M. D., and C. H. Ward. 1984. Reclamation of Contaminated Aquifers: Biological Techniques. In: Proceedings of 1984 Hazardous Material Spills Conference, April 9-12, Nashville, Tennessee. Government Institutes, Inc., Rockville, Maryland.

A.3 Case History C–Retail Gasoline Station, Genesee County, Michigan

A.3.1 Background

In the spring of 1980, gasoline odors were reported in the basement of a bank building in Genesee County, Michigan. As part of a normal program of investigation, the State regulatory agency requested an adjacent service station to check its inventory records and tanks for losses. No losses were documented, but the odors persisted and no other source in the area could be found. At the direction of the State agency, an observation well was constructed on the station property. The well revealed free product gasoline atop the water table, which had evidently leaked into the shallow ground water from one of the station's underground tanks.

A.3.2 Site Description

The subsurface strata in the Genesee County area is characterized by fine glacial sands. Clay is present in the general vicinity of the leak at depths below 30 feet. Observation wells on site showed a static product/water level of 15 to 20 feet below grade before retrieval operations were begun (Yaniga 1984a, 1985).

A.3.3 Nature and Extent of Contamination

Twelve observation wells were used to determine the direction of ground-water flow (to the northwest) and the areal extent of the product plume (Figure A-3). Six wells (Nos. 1, 2, 3, 5, 6, and 7) showed product at thicknesses from 0.5 to 3.8 feet (Yaniga 1984a, 1985).

A.3.4 Corrective Action

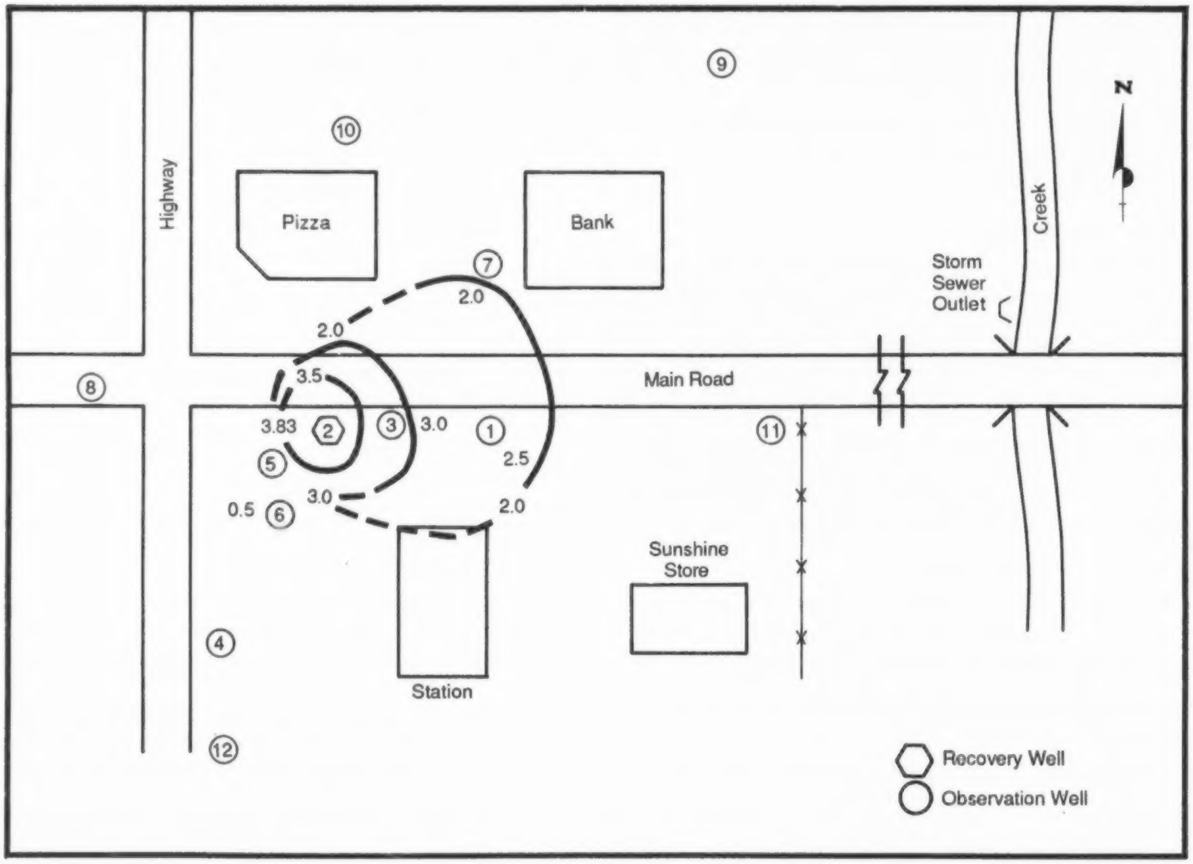
Because the oil company's previous experience in dealing with hydrocarbon contamination of ground water was somewhat limited, initial recovery attempts entailed the use of a vacuum truck to skim the product off the water surface in the well. This resulted in an abundance of water contaminanted with small amounts of product, and gasoline odors in the bank persisted.

Subsequent attempts at product retrieval involved the use of a dual-pump system. Well No. 2 served as the product recovery well. A 3/4-hp explosion-proof water-table depression pump was used to create a cone of depression. Maintenance of a drawdown of approximately 10 feet at the pumping well could achieve a radius of influence of 200 feet. The product (gasoline) flowed to the well and was collected by a product-retrieval pump.

A.3.5 Performance Evaluation

Retrieval operations began in January 1981, and product from observation well No. 7 adjacent to the bank was removed by March 1981. In that time, odor levels were greatly reduced within the structure itself.

Figure A-3. Configuration of the free product plume (Yaniga 1985).



By April 1982, product thicknesses had been reduced to less than 1 foot over a small area, and more than 7000 gallons of gasoline had been retrieved (Yaniga 1984a, 1984b, 1985).

A.3.6 Project Costs

Project costs have not been published; however, cost savings of more than $10,000 per day were reported to result from keeping bank operations open (Yaniga 1984b).

A.3.7 References

Yaniga, P. M. 1984a. Ground-Water Abatement Techniques for Removal of Refined Hydrocarbons. In: Proceedings of the National Conference on Hazardous Wastes and Environmental Emergencies, March 12-14, 1984, Houston, Texas. Hazardous Materials Control Research Institute, Silver Spring, Maryland.

Yaniga, P. M. 1984b. Hydrocarbon Contamination of Ground Water: Assessment and Abatement Testimony presented by Paul M. Yaniga on March 1, 1984, to Hearings of the United States Senate Committee on Environmental and Public Works.

Yaniga, P. M. 1985. Alternatives in Decontamination for Hydrocarbon-Contaminated Aquifers. Ground-Water Monitoring Review, 5(4):40-49.

A.4 Case History D–Retail Gasoline Station, Montgomery County, Pennsylvania

A.4.1 Background

In 1980, several inhabitants of a suburban residential area of Montgomery County, Pennsylvania, noted unusual tastes and odors in their well water. Sampling and analysis of 10 domestic wells by the State regulatory agency attributed the taste and odor problems to dissolved gasoline-type hydrocarbons. The contamination was traced to a low-level, long-term loss of an undetermined amount of unleaded gasoline from an underground storage tank at a nearby service station. Soil and ground water in the area were contaminated, but no free product was found.

A.4.2 Site Description

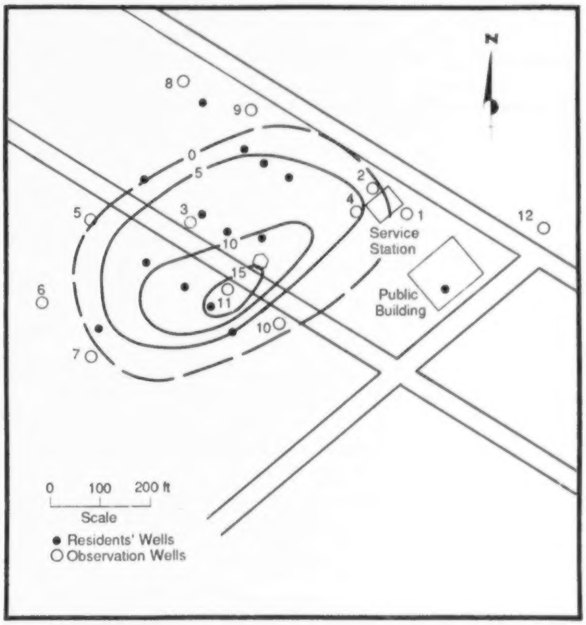
The geology of the impacted area consists of 6 to 7 feet of red-brown silty loam underlain by fractured shale and siltstone. Ground water is encountered 20 to 25 feet below grade in the bedrock system. Domestic water wells penetrate the subsurface 60 to 80 feet.

Ground-water movement through the area is influenced by geologic structure. The direction of ground-water flow is from the northeast to the southwest (i.e., from the area of the service station toward the residents whose water was impacted).

A.4.3 Nature and Extent of Contamination

Twelve monitoring wells were installed in the area as part of a ground-water evaluation program. Samples taken from these wells and existing domestic wells showed the dissolved contaminant plume to extend 200 to 250 feet in a north-south direction and 300 to 350 feet east-west (FMC 1981). Isopach maps of the dissolved product plume (Figure A-4) indicated certain control on its spread by strike and dip of the geologic units (strike: 30°N to 40°E; dip: 12°). Dissolved hydrocarbon concentrations ranged from less than the detection limit (10 ppb) on the periphery of the plume to greater than 15 ppm near the center of the plume. Dissolved oxygen levels within the impacted area were reduced, and naturally occurring hydrocarbon-utilizing bacteria were limited in numbers (Yaniga 1984a, 1985).

Figure A-4. Configurations of the dissolved hydrocarbon plume (Yaniga 1984a).



A.4.4 Corrective Action

The leaking tank, which was found to be pitted with small holes, was excavated from the tank pit area along with the service station's other tanks. Contaminated soil above the tanks was also removed.

The following remedial alternatives were evaluated for abating the existing contamination and for preventing additional contamination of downgradient wells:

- Deepening the wells to case off contamination.
- Providing public water.

- Developing a ground-water decontamination program for the removal of dissolved hydrocarbons.

Geologic conditions indicated some hydraulic connection between the contaminated aquifer and lower water-bearing horizons, such that reconstruction of the wells, could not assure the abatement of well contamination. In addition, any attempt to case off the contamination would restrict further contaminant movement. Public water supplies were not immediately available, nor would their use facilitate the containment or restriction of further contaminant movement. Therefore, a program of hydrocarbon containment and treatment was selected as the most comprehensive alternative.

The ground-water decontamination program was developed on the basis of hydrogeological and geochemical data collected from field and secondary sources. In addition, certain laboratory biocultural studies were conducted to identify dominant hydrocarbon-utilizing species, and bench-scale pilot tests were conducted to determine the effectiveness of air stripping. The resulting program, illustrated in Figures A-5 and A-6, incorporates the following elements:

- Centralized pumping well to contain contaminant movement and induce flow to the recovery location.
- Piping system to convey the contaminated water to an air-stripping tower.
- Air-stripping tower for the removal of volatile organics and the oxygenation of contaminated ground water.
- Infiltration gallery for recirculation of the treated ground water and to facilitate flushing and leaching of adsorbed hydrocarbons back to the recovery well.
- Air-sparging and nutrient-addition wells to facilitate conveyance of necessary oxygen and nutrients into the ground-water system to stimulate the growth of hydrocarbon-utilizing bacteria.
- Regular program of monitoring hydrogeologic, geochemical, and microbiological conditions to determine the success and prognosis of the aquifer cleanup.

Figure A-5. Cross section of the ground-water decontamination program (Yaniga 1984a).

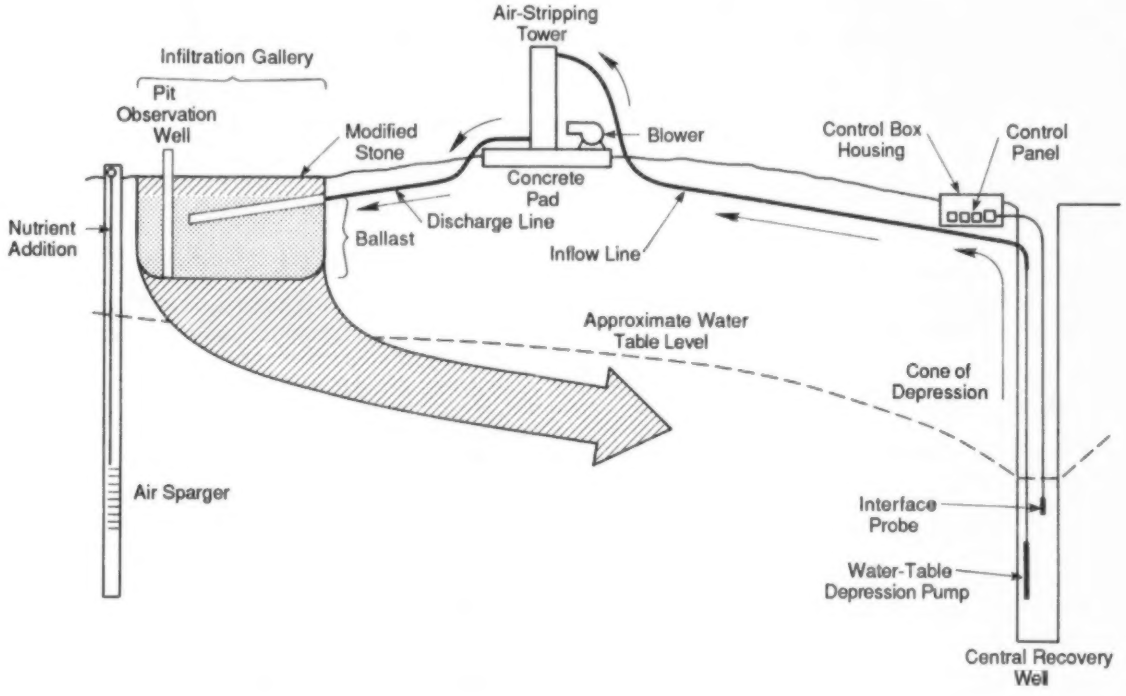
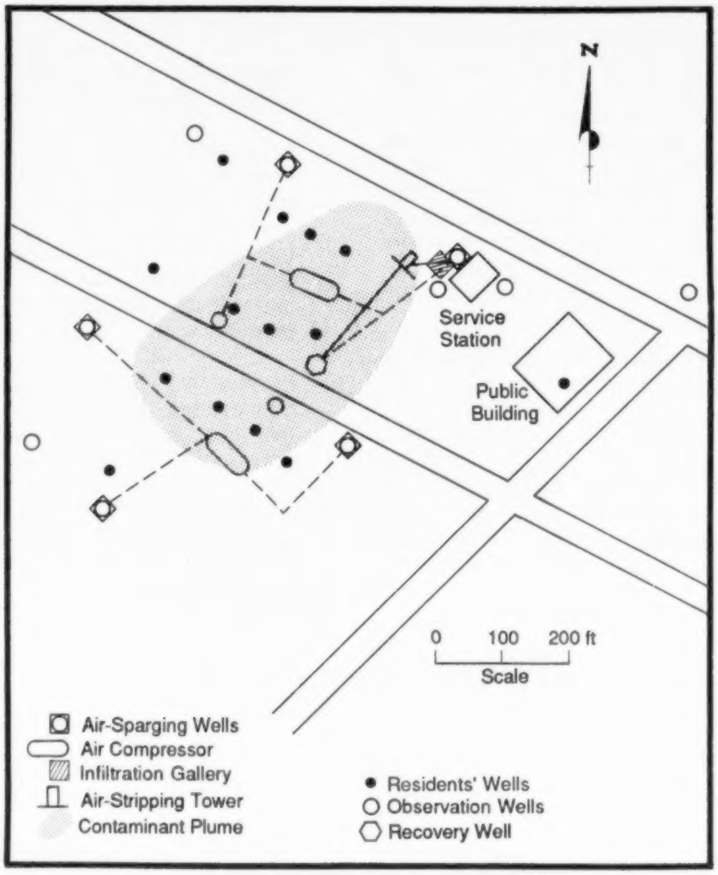

Air-Stripping Tower
Infiltration Gallery
Pit
Observation Well
Modified Stone
Blower
Control Box Housing
Control Panel
Concrete Pad
Nutrient Addition
Discharge Line
Ballast
Inflow Line
Approximate Water Table Level
Cone of Depression
Air Sparger
Interface Probe
Water-Table Depression Pump
Central Recovery Well

Figure A-6. **Plan view of the ground-water decontamination program (Yaniga 1984a).**


N
Service Station
Public Building
0
100
200 ft
Scale
Air-Sparging Wells
Air Compressor
Infiltration Gallery
Air-Stripping Tower
Contaminant Plume
Residents' Wells
Observation Wells
Recovery Well

The following mechanical components were used in the treatment program:

- A 2-hp explosion-proof water-table depression pump equipped with a water-level-control sensing probe and pitless adapter.
- A 24-in.-diameter air-stripping tower (12 ft tall) equipped with a 3-hp blower.
- Two 3-hp air compressors capable of delivering 20 ft^3/min each.
- Six 4 in. x 2 in. carborundum air diffusers.
- 250 ft of 2-in.-diameter ABS pipe for water delivery to and from the air-stripping tower.
- 1200 ft of 1/2-in.-diameter flexible air-pressure line.
- A 20 ft x 30 ft x 10 ft infiltration gallery backfilled with crushed stone ballast.

In implementing the abatement program, it was determined that significant quantities of contaminated soil (silty clay) existed in the former tank pit area. This represented a potential long-term continuing source of gasoline contamination to ground water via leaching; therefore, it was removed for disposal at a secure landfill. The resulting excavation was subsequently converted to an infiltration gallery for the water treated by the air stripper.

Because the impacted area is residential and subject to high volumes of traffic, all electrical leads, water lines, and air-transmission lines were trenched and backfilled. This provided both for the security of these services and for the overall aesthetic acceptability of the system. To accommodate both noise reduction and security, the air compressors were housed in metal sheds, and the air-stripping tower was fenced.

Before the abatement program was initiated, a pump test was conducted to determine the optimum pumping rate and the amount of drawdown required to control ground-water movement within the impacted area. A combined program including analysis of time vs. drawdown and distance vs. drawdown was established. The results indicated an optimum pumping rate of 22 gal/min to maintain 10 feet of drawdown in the recovery well. Results also indicated that the radius of influence could be propagated 300 to 350 feet along the strike and down-dip without dewatering adjacent domestic wells. Pumping effects of the up-dip could only be documented 100 to 150 feet from the pumping well (Yaniga 1984a, 1985). This was far enough to contain the dissolved product plume and to cause it to move toward the pumping well.

A.4.5 Performance Evaluation

Results of the ground-water decontamination program are explained briefly in the following subsections on the performance of the individual components of the system and the reduction of total gasoline-type hydrocarbons achieved. Figure A-7 shows the changes in dissolved hydrocarbon contamination over time in the central, most concentrated area of the dissolved plume. In December 1982, residents' wells showed a 50 to 100 percent reduction in total dissolved gasoline hydrocarbons. Overall, the dissolved plume was reduced in magnitude by 60 to 70 percent within the first year (Yaniga 1984a).

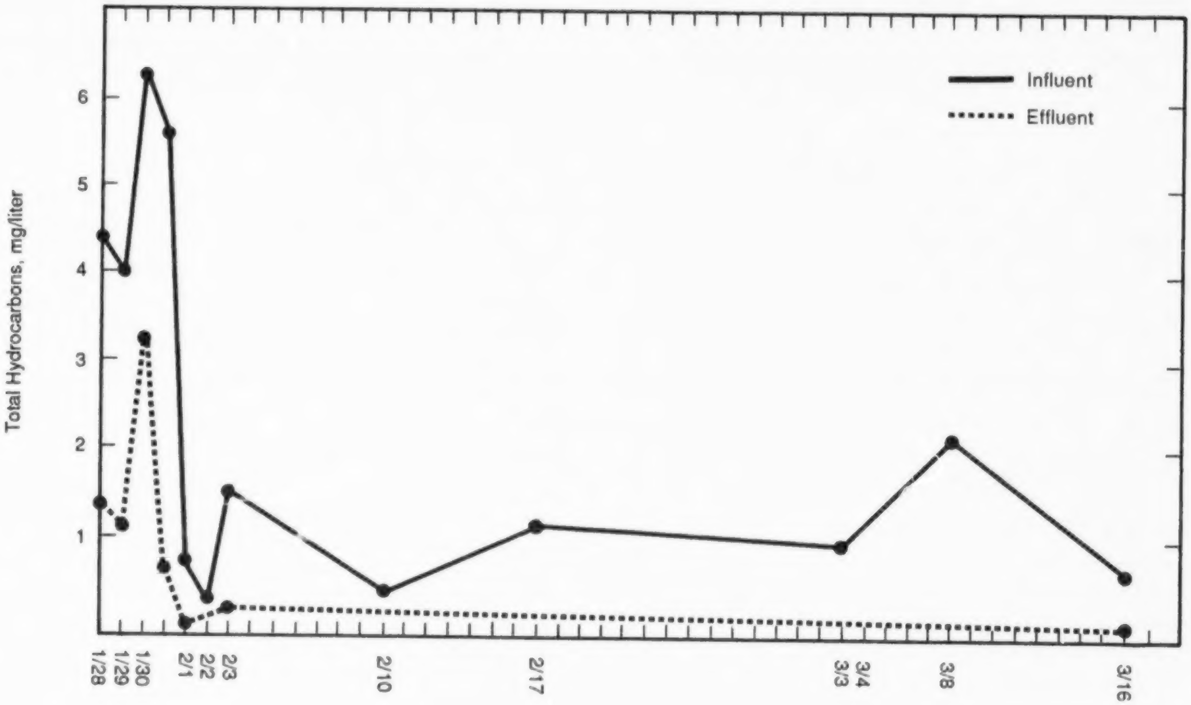
A.4.5.1 Recovery Well

As predicted, the area of influence of the recovery well was greatest along strike and down-dip. Although influence up-dip was less, it was sufficient to contain and reverse the direction of dissolved product movement (Yaniga 1984a, 1985). This asymmetrical configuration for pumping influence is related to the aquifer's homoclinal structure.

A.4.5.2 Air-Stripping Tower

Based on laboratory bench-scale testing, the air stripper was projected to achieve a removal efficiency of 85 to 90 percent for dissolved hydrocarbons. Performance of the air stripping tower, however, exceeded expectations; removal efficiencies of nearly 100 percent were realized for influent concentrations in the 4 to 6 ppm range [i.e., no gasoline hydrocarbons were detected in the air stripper discharge by infrared analysis procedures (0.1 ppm detection limit)] (Yaniga 1984a, 1985).

Figure A-7. **Changes in total hydrocarbon concentrations over time (Yaniga 1985).**



A.4.5.3 Infiltration Gallery

The treated water had to be recirculated through an infiltration gallery to accelerate cleanup of the aquifer. Recirculation aided the physical desorption of hydrocarbons bound to the silty soil and shaly materials and increased the rate of movement of contaminants to the recovery well. Because the treated water was also aerated by the stripping process, oxygen was supplied to the subsurface to accelerate biologic decomposition of residual gasoline hydrocarbons.

The infiltration gallery was excavated in the former tank pit area and backfilled with crushed stone ballast. Monitoring of liquid levels within the gallery showed that it could accommodate a flow of 32,000 gal/day of treated water. Sampling and monitoring for nutrients and tracers added to the gallery indicated water from the gallery flowed initially down-dip and then along strike back to the recovery well (Yaniga 1984a, 1985).

A.4.5.4 Air Sparging

The air-sparging system, which consists of two 3-hp air compressors capable of delivering 5 ft^3/min air to each of six carborundum air diffusers, went on line in March 1982. The air-sparging wells were located on the periphery of the plume; the diffusers were placed in the wells 50 to 55 feet below grade.

For assessment of the effectiveness of the oxygen exchange program, levels of dissolved oxygen (DO) were measured in the observation wells. Before sparging, the levels of DO in wells affected by dissolved gasoline contamination were generally less than 1 mg/liter. Several had DO levels of 0 mg/liter. While the air-sparging system was in operation, dissolved oxygen levels in the sparging wells rose to near saturation levels of 9 and 10 mg/liters. At the periphery of the plume, DO levels rose to 3 to 5 mg/liter. Dissolved oxygen levels within the core area of the plume rose to 2.5 to 3 mg/liter in approximately 6 weeks (Yaniga 1984a, 1985).

Adequate oxygen supply proved to be a limiting factor in the growth of hydrocarbon-degrading bacteria. The air-sparging system was eventually replaced by the continuous addition of an oxygen-enhancement solution to the injection gallery. Dissolved oxygen levels within the plume subsequently increased to 4 to 8 mg/liter (FMC 1981).

A.4.5.5 Nutrient Addition

In March 1982, nutrients began to be added to the ground water to stimulate the growth of indigenous bacteria. The nutrient broth contained a mixture of ammonium chloride, sodium phosphates, and various mineral salt tracers to track the spread and movement of the nutrients through the aquifer system. Nutrients were added to the treated ground water in batches and injected through the gallery.

Monitoring of the tracers indicated slow ground-water migration from the infiltration pit along strike to the recovery well (Yaniga 1984a, 1985). Because nutrient diffusion rates were slower than desired, the nutrient-addition program was modified to incorporate the use of additional observation wells and the more frequent addition of nutrients. These modifications increased the effectiveness of the bacteria in consuming the hydrocarbons.

A.4.6 Project Costs

Project costs have not been published.

A.4.7 References

FMC Corporation. 1981. Case History—Leaking Underground Gasoline Storage Tank. Promotional Literature. Princeton, New Jersey.

Yaniga, P. M. 1984a. Groundwater Abatement Techniques for Removal of Refined Hydrocarbons. In: Proceedings of the National Conference on Hazardous Wastes and Environmental Emergencies, Houston, Texas, March 12-14, 1984. Hazardous Materials Control Research Institute, Silver Spring, Maryland.

Yaniga, P. M. 1985. Alternatives in Decontamination for Hydrocarbon-Contaminated Aquifers. Ground-Water Monitoring Review, 5(4):40-49.

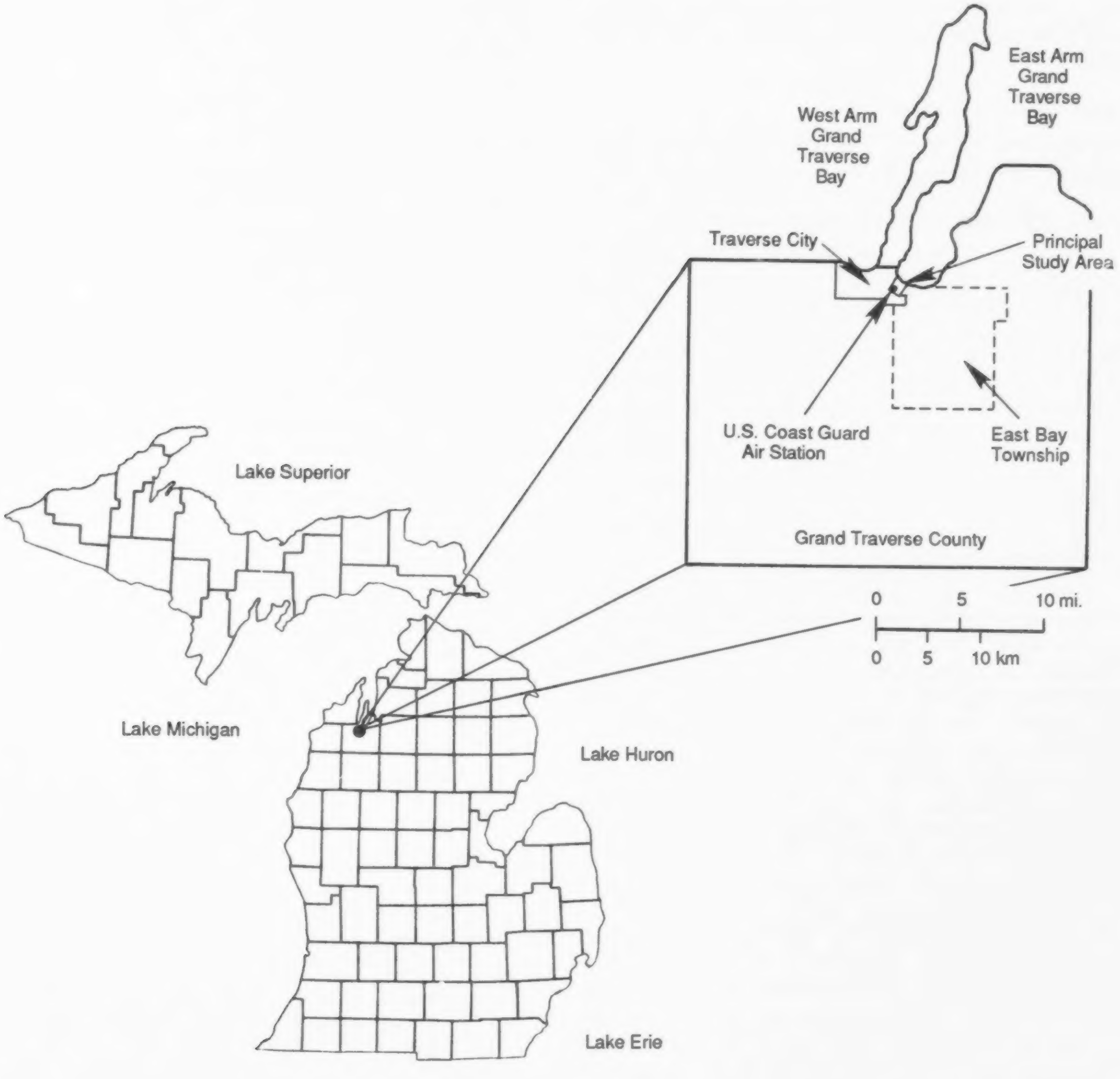
A.5 Case History E–U.S. Coast Guard Air Station, Traverse City, Michigan

A.5.1 Background

In July 1942, the United States Navy established an Air Station at Traverse City, Michigan, a small isolated community in the northwestern section of the Lower Peninsula (Figure A-8). The purpose of the Air Station was to conduct highly classified research and development of pilotless drone aircraft. This research effort was suspended in 1944. When the war ended, the Air Station was turned over to the U.S. Coast Guard (USCG) to serve as a major Search and Rescue base for Lake Superior, Lake Huron, and the upper portion of Lake Michigan.

In 1979, during the removal of two fuel farms preparatory to the installation of a new system, soil contamination was discovered in the jet fuel (JP-4) storage area. This area was located some 1500 feet upgradient and to the north of an area that was ultimately implicated as the "geographical origin" of the plume. The aviation fuel (115/145) farm immediately adjacent to the "geographical origin" of the plume was excavated at the same time, and little

Figure A-8. **Location of U.S. Coast Guard Air Station, Traverse City, Michigan (Sammons and Armstrong 1986).**


East Arm
Grand
Traverse
Bay
West Arm
Grand
Traverse
Bay
Traverse City
Principal
Study Area
U.S. Coast Guard
Air Station
East Bay
Township
Grand Traverse County
0
5
10 mi.
0
5
10 km
Lake Superior
Lake Michigan
Lake Huron
Lake Erie

indication of any leakage was found. Some odor was noted in the soil, but laboratory analyses did not confirm gross contamination.

In 1979 and 1980, residents in the Avenue E area of the Pine Grove Subdivision of East Bay Township complained to the local health department that the water from their wells was discolored, foamed, tasted bad, and had a foul odor. The first residence reporting the problem is located 1200 feet to the northeast of the Coast Guard Air Station (CGAS). At that time there was no explanation for the contaminated wells, and the health department did not test for any of the possible organic contaminants. Later in 1980, the Michigan Department of Natural Resources (MDNR) did a limited hydrogeologic study in the area and concluded that the source of the contamination was from some unspecified site on the CGAS. In May 1982, the Coast Guard was notified of these findings.

Subsequent internal investigations by the USCG revealed that an aviation fuel spill incident had occurred 11 years earlier (in November or December 1969) when a flange in an undergound pipeline beneath a 115/145 high-octane aviation gasoline fueling station failed. The failure resulted in a loss of approximately 2000 gallons of product over a 12-hour period.

A.5.2 Site Description

Descriptions of the site's stratigraphy and hydrogeology were not available.

A.5.3 Nature and Extent of Contamination

In June 1982, the Coast Guard retained the U.S. Geological Survey (USGS) to conduct a thorough hydrogeological study of the area to define the extent of the contaminant plume and to determine its source. By April 1983, the USGS had determined the direction of ground-water flow through the area (to the northeast) and had tentatively identified the boundaries of the plume. Although the USGS was unable to determine the source of the contaminants, they did conclude that the majority of the contaminants identified were related to components in fuels. They also indicated that some chlorinated compounds were present.

In November 1983, the Coast Guard contracted the University of Michigan (UM) to make a scientific study of the site. The objectives of this study were to analyze the temporal variation of the plume and to determine positively the origin(s) of the contamination. The UM study identified benzene and toluene as the components in the plume presenting the greatest health risk. The largest concentrations of these compounds occurred in the vicinity of the Hangar/Administration Building (HAB) at the geographical head of the plume (Figures A-9 and A-10), although significant amounts of some compounds (e.g., benzene) were found at some distance downgradient. Other chemicals also were found in the plume, but at smaller concentrations and reduced distributions (Sammons and Armstrong 1986).

From the HAB, the plume followed ground-water flow to the northeast and off the base, passed under an industrial park, and turned slightly north. It narrowed as it passed underneath Parsons Road and widened out again under Avenue E (Figure A-11). The plume was approximately 4300 feet long and varied from 180 to 400 feet in width. Its vertical dimension ranged from 25 to 80 feet (Sammons and Armstrong 1986).

Small concentrations of benzene and toluene were detected in the water of East Bay. The USGS reported maximum benzene values of 20 µg/liter and maximum toluene values of 3.1 µg/liter approximately 330 feet from shore (Sammons and Armstrong 1986).

Both the UM study and the USGS study reported numerous measurements of organics in the soils at the Air Station. The UM study found the following maximum concentrations: benzene, 25.4 µg/liter; toluene, 27.6 µg/liter; and xylene, 299 µg/liter. Analyses for seven other hydrocarbons showed negative results (Sammons and Armstrong 1986). Analysis of soil borings indicated that much of the organic material was retained in the soil in a 6- to 12-inch thick layer in the capillary zone immediately above the water table. This zone served as a continuing source of ground-water contamination.

In February 1985, new hydrocarbon contamination was discovered at the JP-4 fuel farm south of the HAB. The four fiberglass underground storage tanks at the station were tested, and three of them were found to be leaking.

A.5.4 Corrective Action

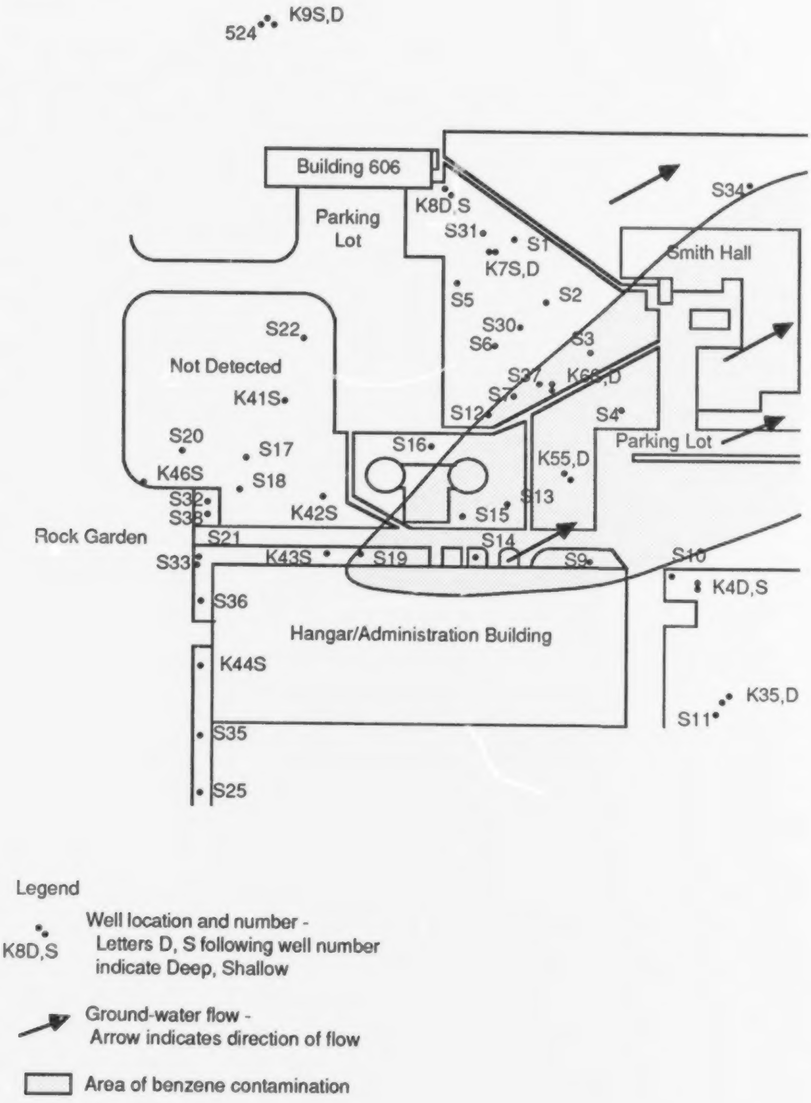
Hydrocarbon contamination of the soil and ground water at the Air Station initially occurred in 1969 and remained undetected until 1979. Contaminated soil was subsequently removed from the JP-4 storage area under the direction of the MDNR. The three leaking tanks discovered in 1985 were also removed.

After the various long-term treatment or cleanup options available had been considered, it became clear that the first step in any remedial program would be to decrease or stop further movement of contaminants off U.S. Coast Guard property. This option was judged to have several advantages:

- Reduction of any possible increase in risk to human populations that may have been related to fuel-based contaminants present in the ground water.
- Promotion of reductions in contaminant concentrations in the ground water either by dilution or the possible biodegradation of fuels by indigenous microbial populations present in the subsurface soil-water system.
- Provision of a better opportunity (e.g., more time) to efficiently select and design appropriate method(s) for dealing with the contaminants present in the geographical origin of the plume.

A containment system consisting of seven extraction wells spaced laterally across the plume was constructed in the east-northeast area of the Air Station to block further migration of the plume offsite. Six-inch auger-drilled wells with full 10-slot stainless steel screens running from the top of the aquifer to the clay confining layer at the bottom were installed. The full-screen configuration was necessary to capture contaminants that were present throughout the vertical extent of the aquifer.

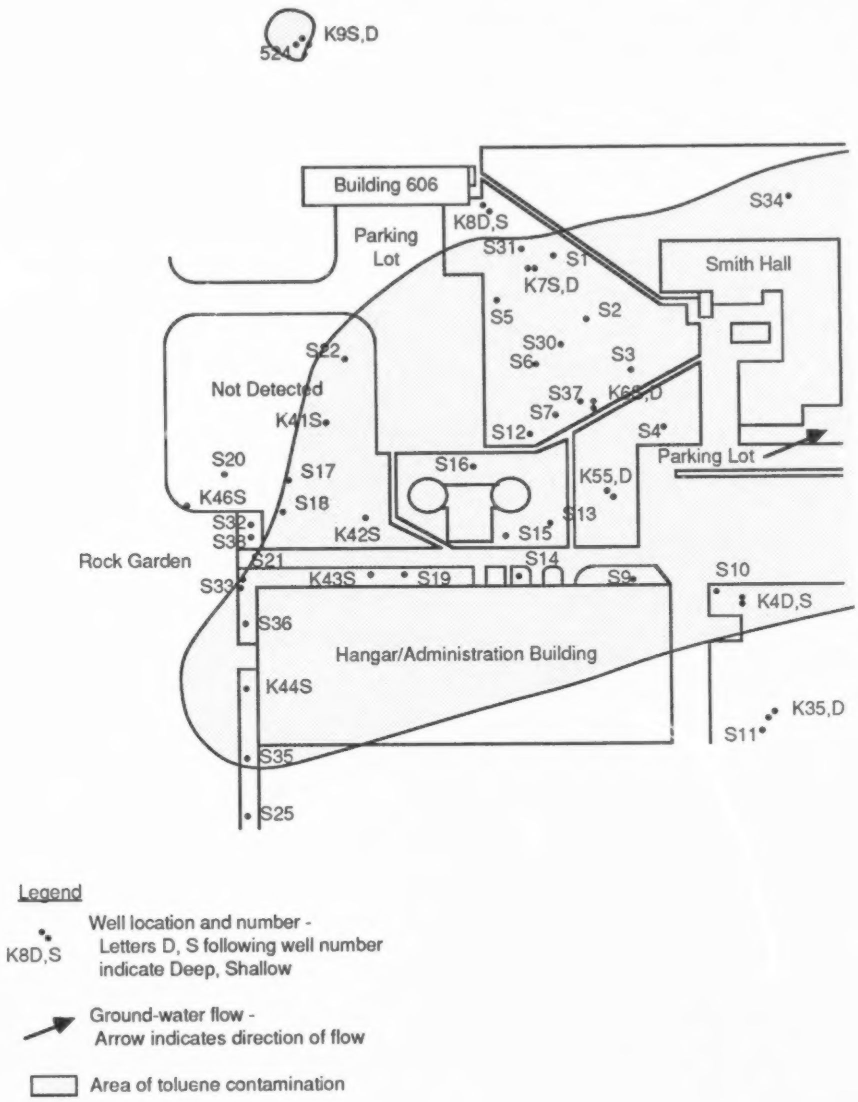
Figure A-9. **Area of benzene contamination near the Hangar/Administration building (Sammons and Armstrong 1986).**


524
K9S,D
Building 606
Parking Lot
K8D,S
S31
S1
K7S,D
S5
S2
S34
Smith Hall
S22
Not Detected
S30
S6
S3
S37
K66,D
K41S
S7
S12
S4
S20
S17
S16
Parking Lot
K55,D
K46S
S18
S32
S38
K42S
S15
S13
Rock Garden
S21
S14
S33
K43S
S19
S9
S10
K4D,S
S36
Hangar/Administration Building
K44S
K35,D
S11
S35
S25
Legend
K8D,S
Well location and number - Letters D, S following well number indicate Deep, Shallow
Ground-water flow - Arrow indicates direction of flow
Area of benzene contamination

The water produced from the extraction well system was piped to a carbon treatment system, which consisted of four 20,000-lb carbon reactors. The carbon reactors were specified to reduce the levels of benzene and toluene in the water to less than 1 µg/liter. The extracted water was discharged to the Traverse City Publicly Owned Treatment Works. Costs for processing the discharge were estimated at between $4,000 and $10,000 per month (Sammons and Armstrong 1986).

To monitor the effectiveness of the containment system, a network of five monitoring wells was constructed downgradient of and outside the zone of influence of the extraction well system. Ground-water samples were collected by standard field procedures for the collection of volatiles and were analyzed within a few hours of collection. Five sample pumps were placed in each monitoring well: one each at the top and bottom of the saturated zone and three at equidistant imtermediate points.

Figure A-10. Area of toluene contamination near the Hangar/Administration building (Sammons and Armstrong).

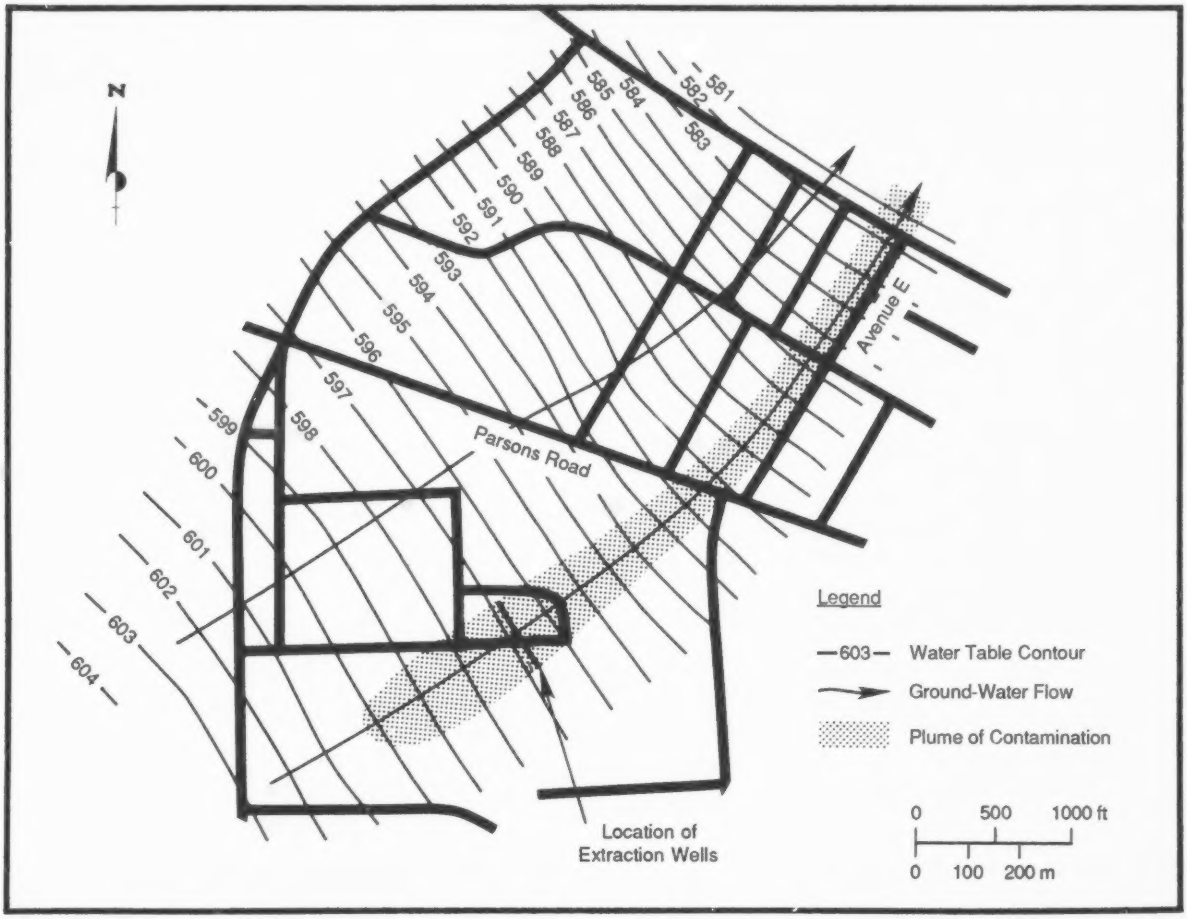

K9S,D
524
Building 606
Parking Lot
K8D,S
S31
S1
K7S,D
S5
S2
S30
S6
S3
S37
K68,D
S7
S12
S4
Smith Hall
Parking Lot
S34
S22
Not Detected
K41S
S20
S17
K46S
S18
S32
S38
K42S
S16
K55,D
S13
S15
S14
Rock Garden
S21
S33
K43S
S19
S9
S10
K4D,S
S36
Hangar/Administration Building
K44S
K35,D
S11
S35
S25
Legend
K8D,S
Well location and number - Letters D, S following well number indicate Deep, Shallow
Ground-water flow - Arrow indicates direction of flow
Area of toluene contamination

A.5.5 Performance Evaluation

Toluene and benzene levels in the downgradient monitoring wells were monitored in one of the five wells (M2/TG12) on a daily basis for the first 8 weeks and on a biweekly basis thereafter. The other four wells are monitored once a week.

Figure A-12 shows the concentrations of benzene and toluene in Well M-2 (immediately downgradient of the extraction well system) from April to December 1985. Toluene levels decreased from a baseline level of 10,329 ppb to less than 10 ppb in approximately 100 days (Sammons and Armstrong 1986). The decrease in toluene levels together with the accompanying rise in benzene between May and July could be attributed to the demethoxylation of toluene to benzene by microbial activity. The increase in benzene from October to December is attributed to the appearance of a red slime (oxidized iron compounds and complexes, mineral deposits, and

Figure A-11. Offsite migration of the contaminant plume (Sammons and Armstrong 1986).


N
581
582
583
584
585
586
587
588
589
590
591
592
593
594
595
596
597
598
599
600
601
602
603
604
Avenue E
Parsons Road
Legend
—603— Water Table Contour
Ground-Water Flow
Plume of Contamination
0 500 1000 ft
0 100 200 m
Location of Extraction Wells

biomass), which plugged pump screens, coated the inside of the piping system, and reduced the hydraulic capacity of the system.

A.5.6 Project Costs

Project costs have not been published.

A.5.7 References

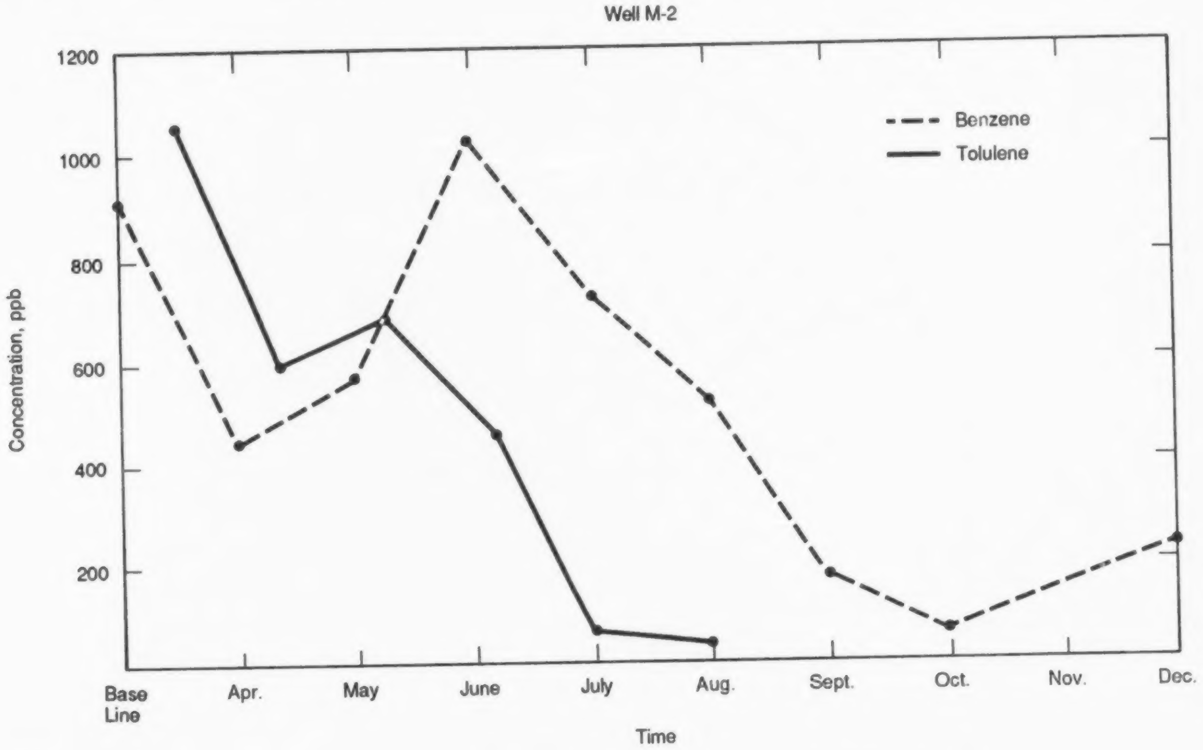
Sammons, J. H., and J. M. Armstrong. 1986. Use of Low Flow Interdiction Wells to Control Hydrocarbon Plumes in Groundwater. In: Proceedings of the National Conference on Hazardous Wastes and Hazardous Materials, Atlanta, Georgia, March 4-6, 1986. Hazardous Materials Control Research Institute, Silver Spring, Maryland.

A.6 Case History F–Bulk Fuel Storage and Distribution Center

A.6.1 Background

The loss of more than 200,000 gallons of fuel oil from a bulk storage and distribution center was first detected via inventory reconciliation. The loss, which initially went unnoticed because of the high volume of fuels turnover at the facility, was originally believed to be the result of a shortage or theft. Further investigations by the owner, however, revealed a leak in one of the facility's underground transmission lines that served a seldom-used remote loading rack. A cursory investigation concluded (incorrectly) that the product had migrated miles from the area. Consequently, retrieval of the lost product did not begin until 2 years later, when fuel oil-type hydrocarbons were encountered during the construction of a downgradient well.

Figure A-12. Concentrations of benzene and toluene in Well M-2 (Sammons and Armstrong 1986).



A.6.2 Site Description

The fuel storage depot, which is situated in a light industrial and commercial area, is immediately adjacent to a local quarry operation (Figure A-13). The site is underlain by a silty-clay overburden and limestone-dolomite bedrock. Depth to bedrock varies from 10 to 50 feet over short lateral distances, which indicates the presence of a pinnacle-and-trough rock profile. The dolomite is prone to the evolution of solution channels, and deep residual soil has developed along joint sets, rock fractures, and certain bedding planes. The dominant joint set is oriented in a NNW-SSE direction.

A shallow aquifer is present at 50 to 70 feet below grade, and a second, much deeper, aquifer is present at a depth of 200 feet. Ground-water flow, which is controlled by the dominant joint set, is west to northwest toward the adjacent quarry. One local industry relies solely on ground water (approximately 150,000 gal/day) for all manufacturing processes. This causes some local impact on ground-water movement (i.e, induced flow).

A.6.3 Nature and Extent of Contamination

To define the impact of the product loss on the local ground-water regime, a detailed hydrogeologic investigation was conducted during the summer of 1982. Six 4-inch observation wells were constructed along the dominant joint set at intervals of 100 to 150 feet and depths of 70 to 110 feet. Two additional observation wells were located off the dominant joint set normal to the trend. The defined free-product plume measured up to 60 feet thick, 900 feet long, and 300 feet wide. True product thickness reached its maximum in the vicinity of Well G-2 (Figure A-14). The predominant direction of free-product migration was along the dominant joint set to the northwest (Yaniga and Demko 1983).

A.6.4 Corrective Action

The immediate response to the pipeline break entailed repair and rerouting of the plumbing. Product retrieval was not initiated until 2 years later.

Aquifer testing prior to product-recovery attempts indicated wells constructed to the 70- to 100-foot

Figure A-13. **Location of bulk fuel storage and distribution center (Yaniga and Demko 1983).**

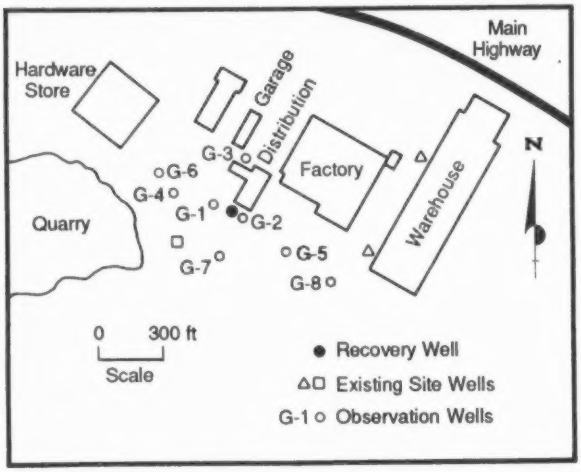
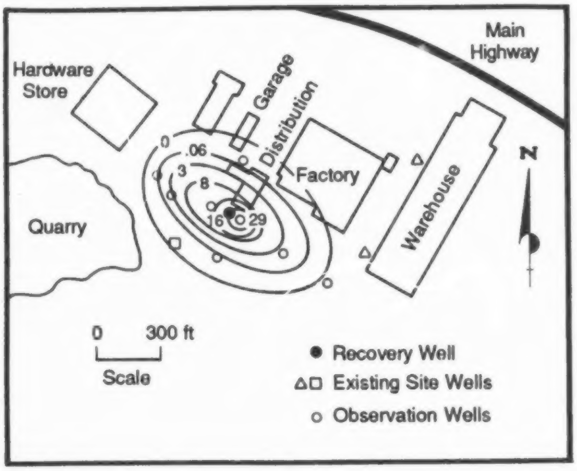

Main Highway
Hardware Store
Garage
Distribution
G-3
oG-6
G-4
Factory
G-1
G-2
Quarry
Warehouse
N
G-7
G-5
G-8
0 300 ft
Scale
● Recovery Well
△□ Existing Site Wells
G-1 ○ Observation Wells

Figure A-14. **Configuration of the free product plume (Yaniga and Demko 1983).**


Main Highway
Hardware Store
Garage
Distribution
0
.06
3
8
16
29
Factory
Quarry
Warehouse
N
0 300 ft
Scale
● Recovery Well
△□ Existing Site Wells
○ Observation Wells

depth could not control the total product plume from any one location (Yaniga and Demko 1983). Consequently, a 12-inch-diameter recovery well was constructed in the vicinity of Well G-2 to a depth of 240 feet.

Water table control and free product collection were achieved by creating a cone of depression with a 2-hp explosion-proof, water-table depression pump. By maintaining a minimum of 20 feet of drawdown at the pumping well, a radius of influence along the dominant joint set trend of approximately 450 feet was achieved. Free product flowing into the well along the created cone of depression was collected by a product-retrieval pump, which operates by a sensing probe that differentiates between water and product. An in-line transfer pump was designed into the system to provide additional delivery head and to transfer the product to a remote storage area.

Water pumped from the recovery well contained dissolved organic constituents at levels below the discharge criteria of the local regulatory agency. An infiltration gallery was constructed within the influence of the recovery well to recirculate the water to the ground-water system.

A.6.5 Performance Evaluation

The free-product recovery system constructed at this site successfully reversed the migration of the fugitive fuel. Reusable fuel-oil-type hydrocarbons were recovered at an average rate of 500 to 700 gal/day (Yaniga and Demko 1983).

A.6.6 Project Costs

Project costs have not been published.

A.6.7 References

Yaniga, P. M., and D. J. Demko. 1983. Hydrocarbon Contamination of Carbonate Aquifers: Assessment and Abatement. In: Proceedings of the Third National Symposium on Aquifer Restoration and Ground-Water Montoring. National Water Well Association, Worthington, Ohio.

A.7 Case History G–Midwestern Laboratory Facility

A.7.1 Background

Vapors were discovered in a laboratory building at a midwestern industrial facility. Investigation of this problem traced the source of the vapors to a below-ground tank vault adjacent to the building. The vault, which contained seven 6000-gallon tanks, was used for storing clean fuel oils and waste solvents from the laboratory facility. Testing of the tanks in the vault revealed that two of the seven were leaking.

A.7.2 Site Description

The vault, which measures 25 feet wide, 70 feet long, and 12 feet deep, was constructed in a natural clay strata (glacial till) and backfilled with medium pea gravel. Descriptions of the site's stratigraphy and hydrogeology are not available.

A.7.3 Nature and Extent of Contamination

A series of monitoring wells were drilled in the vault and in the area adjacent to the vault. Free product was found to be confined to the vault area. Ground-water contamination was confined primarily to the vault, but some dissolved hydrocarbons were detected in the clay strata immediately adjacent to the tank. Soils throughout the vault were saturated with aromatic and aliphatic hydrocarbons. Total contamination was calculated to be 655 gallons of free product (solvent/fuel mixture) and 300 to 900 gallons of adsorbed hydrocarbons (Brenoel and Brown 1985; FMC 1984).

A.7.4 Corrective Action

The first phase of remediation was removal of free product. Water was pumped from the sump well at 15 to 25 gal/min with a surface-mounted, explosion-proof pump to depress the water table and allow free product to collect. Free product was separated/ recovered from the well with a dual-pump system. Clean water from this operation was injected into the vault to sweep the contaminated area. A total of 700 gallons of free product were recovered in this manner (Brenoel and Brown 1985; FMC 1984).

The second phase of remediation involved treatment of the contaminated fill and ground water. The total hydrocarbon concentration in the ground water prior to free-product recovery was 22,700 ppb; this concentration increased to approximately 45,000 ppb during free-product recovery because of the increased circulation of the ground water. The vault contained approximately 22,000 gallons of ground water, which represented 4 to 10 lb of dissolved hydrocarbons (Brenoel and Brown 1985; FMC 1984). This amount could not be significantly reduced, however, without removing the source of the dissolved fraction, i.e., the material adsorbed in the fill.

Two options were considered for the second phase of remediation: 1) pumping and treating of ground water with carbon adsorption or air stripping, and 2) biostimulation. The first option was not chosen for the following reasons:

1) The quantity of carbon needed to treat all of the contaminated ground water would be too costly.
2) Air stripping would require special engineering and permitting because of concerns with atmospheric discharges.
3) Time was a problem; downtime had to be minimal because this was a high-activity area.
4) Carbon adsorption and air stripping would not effectively remove the adsorbed material.

Biostimulation was chosen for the second phase of remediation because of its cost-effectiveness, timeliness, efficiency, and minimal equipment requirements. The basic elements of the biostimulation process installed at this site included 1) a ground-water circulation system to sweep the contaminated area (i.e., a system of injection and recovery wells), and 2) nutrient and oxygen injection capabilities.

Bacterial counts were taken at the site before the program was initiated to verify the presence of an active bacterial community. Two types of counting procedures were used, one for the total bacteria and one for specific hydrocarbon degraders. Counts taken on successive days were as follows (Brenoel and Brown 1985):

Total bacteria	Hydrocarbon degraders
420,000	5,400
300,000	6,100

In the laboratory, the addition of nutrients to ground water from the vault increased both total and hydrocarbon-degrading bacteria by several orders of magnitude. These data confirmed the feasibility of implementing biostimulation at the site.

The ground-water recirculation system, which was designed to sweep the entire vault, consisted of four injection wells and a pumping well. The injection wells were screened throughout their total depth. Ground-water pumping rates averaged 15 to 25 gal/min for most of the project.

The nutrients required for effective stimulation of bacteria and controlled degradation of hydrocarbons are nitrogen, phosphorus, trace minerals, and oxygen. Two formulations were used at the site: a blend of ammonium chloride and sodium phosphates and a formulated oxygen-enhancement solution. Because the available oxygen level is critical to maintaining a rapid rate of degradation, the oxygen-enhancement solution was added continually for the entire biostimulation phase. The nitrogen/phosphorus (N/P) blend was added to the four injection wells in batches to maintain N/P levels of 100 to 200 ppm.

The nutrient addition caused a 10-fold increase in total bacteria and a 200-fold increase in hydrocarbon degraders (Brenoel and Brown 1985; FMC 1984).

The hydrocarbon concentration dropped significantly during the course of biostimulation. The greatest drop occurred in the first 42 days of operation, which paralleled the consumption of nutrients (Brenoel and Brown 1985; FMC 1984).

At the end of the biostimulation phase, the injection rate in the vault decreased from 15 to 25 gal/min to as low as 1.5 gal/min, apparently the result of movement of silts through the backfill and degradation of cement in the vault causing a buildup of silicates and silts at the well screens. Because of concern with the ability to supply nutrients at the low injectivity and because the hydrocarbon levels had been significantly reduced, the biostimulation phase of remediation was terminated.

The final phase of remediation involved the use of an activated carbon system for further reduction of residual hydrocarbons in the ground water. The system consisted of two activated carbon tanks plumbed in series. Influent to the carbon columns was via a surface-mounted pump at the vault sump. The effluent was recirculated through injection well No. 3 for continued sweeping of the vault. This design minimized site reconstruction and equipment.

During the operation of the carbon column, the influent hydrocarbon concentration increased. This increase was traced to a leaking line between the laboratory and the vault that had not been detected and repaired during the initial phase of remediation. Consequently, a slow, low-volume leak had continued throughout the remediation program. The leak contaminated water entering the vault, but it did not add significant quantities of hydrocarbons. Upon repair of the leak, influent hydrocarbon levels decreased because the carbon columns were able to remove the residual dissolved hydrocarbons. The rapid drop in influent hydrocarbon levels after the leak was repaired demonstrates that it was no longer contaminating the fill in the vault. After an additional 2 months of carbon column operation, dissolved hydrocarbon levels were reduced to less than 10 ppb (Brenoel and Brown 1985; FMC 1984).

A.7.5 Performance Evaluation

The remediation program eliminated the soil contamination in the vault and significantly reduced the ground-water contamination. This project illustrates how an integrated approach to site remediation can solve severe contamination problems. Each stage of remediation was chosen for maximum efficiency in dealing with the contamination problem. A well-designed free-product-recovery system eliminated the severe, free-floating layer. Biostimulation was effective in removing the adsorbed and most of the dissolved hydrocarbons. Finally, carbon adsorption was also effective in removing low-level, residual, dissolved hydrocarbons. This integrated approach speeded up the recovery and reduced costs.

A.7.6 Project Costs

Project costs have not been published.

A.7.7 References

Brenoel, M., and R. A. Brown. 1985. Remediation of a Leaking Underground Storage Tank With Enhanced Bioreclamation. Presented at the NWWA 5th National Symposium and Exposition, Aquifer Restoration and Groundwater Monitoring, Columbus, Ohio, May 21-24, 1985. National Water Well Association, Inc., Worthington, Ohio.

FMC Corporation. 1984. Case History -- Midwestern Industrial Facility. Promotional Literature. Princeton, New Jersey.

A.8 Case History H–Chemical Pipeline

A.8.1 Background

On August 16, 1983, investigation into a pressure loss in the water main at an industrial facility led to the discovery of a ruptured methylene chloride pipeline in proximity to the water main. The buried pipeline had leaked an undetermined amount of methylene chloride into the soil and ground water before the break was discovered.

A.8.2 Site Description

Descriptions of the site's stratigraphy and hydrogeology are not available.

A.8.3 Nature and Extent of Contamination

Monitoring wells installed in the vicinity of the pipeline break indicated that contamination was confined to a clay layer at the 20-foot level and had not reached an aquifer at the 100-foot level. Coarse gravel lenses and utility lines in the area, however, had permitted methylene chloride to migrate laterally with little resistance.

A.8.4 Corrective Action

Emergency response to the spill involved only containment. Trenches were constructed in the vicinity of the pipeline break to intercept the contamination. Free product in the trenches was collected with vacuum equipment and staged in vessels for eventual onsite treatment.

The alternatives investigated for environmental restoration of the site once the spill was contained included excavation and disposal, physical containment, gravity collection, ground-water pumping, and biological treatment. A combination of these alternatives was determined to be the most effective means for site remediation.

The first stage of site remediation entailed excavation of the highly contaminated soil. Approximately 160 yd^3 of soil (1.1 percent of the total contaminated soil) was removed from the site to a Class A secure landfill (Flathman and Caplan 1986; Flathman et al. 1985).

After the highly contaminated soil was removed, pumping wells were installed, and contaminated ground water was pumped to the surface by both positive-placement and suction-lift techniques.

Packed-column air stripping was considered the preferred physical treatment technology for removing methylene chloride from recovered ground water because of the compound's strippability and the relatively maintenance-free operation of the unit. Also, the State regulatory agency did not require vapor-phase scrubbing to control air emissions from the stripping tower.

The recovered ground water was characterized and bench-scale tested to determine necessary pretreatment requirements. A schematic diagram of the physical treatment system, which was designed to operate at a flow rate of 10 to 15 gal/min, is presented in Figure A-15. The recovered ground water was first pumped through a downflow mixed-media filter (anthracite, silica sand, and pea gravel) to remove sand and other particulate matter. It was then piped to a separation tank with a residence time of 14 hours, which allowed the denser methylene chloride to separate from the water by gravity. Pure product was recovered from the bottom of the tank. Supernatant containing up to 150 ppm dissolved methylene chloride was then pumped through a skid-mounted shell-and-tube heat exchanger to raise the temperature of the water from 10°C to more than 40°C. The heated water was then pumped to the top of a 9-foot air-stripping column packed with 2-inch ceramic Raschig rings for removal of soluble methylene chloride. The tower operating temperature was maintained between 27°C and 60°C. Effluent containing less than 20 ppm methylene chloride was discharged to the facility's onsite wastewater treatment plant for further processing. Contaminant-laden air was vented to the atmosphere through a 10-foot stack.

After 2 months of operation, air stripping reduced the concentration of methylene chloride in the ground water by an estimated 97 percent (Flathman and Caplan 1986; Flathman et al. 1985). It became increasingly more difficult to remove the residual contamination by physical means, however, and biological techniques were considered.

Bench-scale biodegradation studies indicated the presence of a naturally occurring microbial population capable of degrading methylene chloride; however, inorganic nitrogen and phosphorus nutrient additions would be necessary. The biological treatment system, illustrated in Figure A-16, consisted of a recovery/injection system and a modified activated-sludge system. The recovery system was used to withdraw contaminated ground water for above-ground treatment. Supernatant containing adapted microorganisms from the activated sludge process was reinjected into the subsurface environment, which created a closed-loop system. Biodegradation of methylene chloride occurred in situ as well as above ground. Biological treatment commenced on the 82nd day of field operations and was suspended after 41 days because of the onset of winter conditions.

A.8.5 Performance Evaluation

Figure A-17 presents the reduction in methylene chloride concentration obtained in monitoring well B-5 (located 20 feet downgradient of the pipeline break) during the 3-month operation of the air stripper. After 2 months, methylene chloride had been reduced 97 percent (from 9300 ppm to 300 ppm) (Flathman and Caplan 1986, Flathman et al. 1985).

Biodegradation of methylene chloride in the ground water was rapid. A 50 percent reduction in methylene chloride concentration was observed in monitoring well B-5 within 8 days (Figure A-18). This reduction in methylene chloride was accompanied by a corresponding increase in chloride concentration. When biological treatment was suspended at the end of the fourth month, 97 percent of the residual contamination had been degraded for an overall reduction in methylene chloride of greater than 99.9 percent (Flathman and Caplan 1986; Flathman et al. 1985).

A.8.6 Project Costs

Project costs have not been published.

Figure A-15. Schematic diagram of the physical treatment system (Flatham and Caplan 1986).

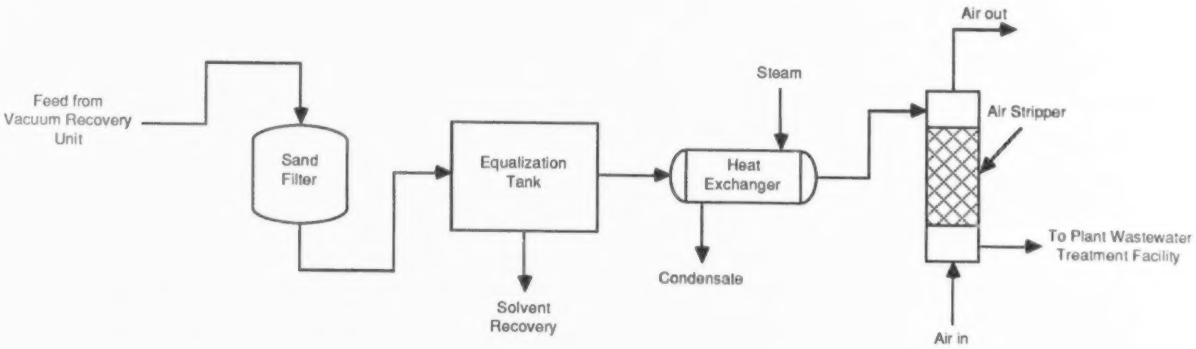


Figure A-16. Schematic diagram of the biological treatment system (Flatham and Caplan 1986).

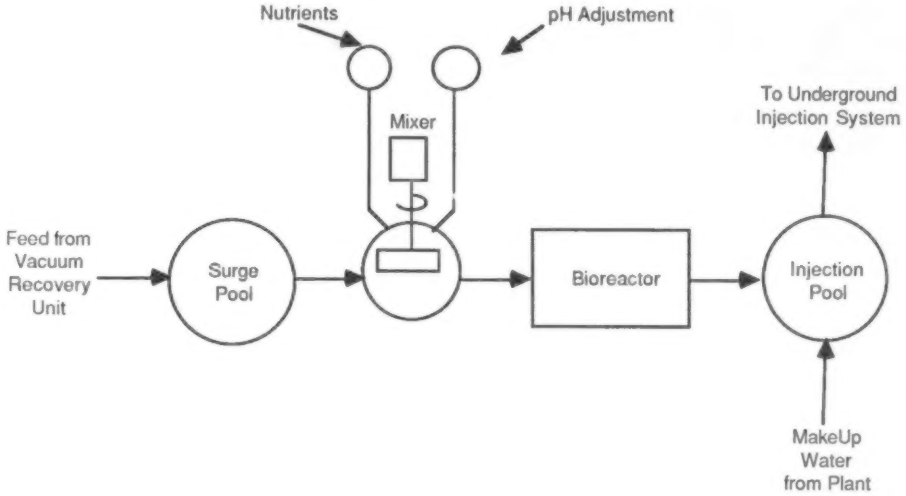

Nutrients
pH Adjustment
Mixer
To Underground Injection System
Feed from Vacuum Recovery Unit
Surge Pool
Bioreactor
Injection Pool
MakeUp Water from Plant

Figure A-17. Reduction in methylene chloride concentration in well B-5 achieved during air stripping (Flathman and Caplan 1986).

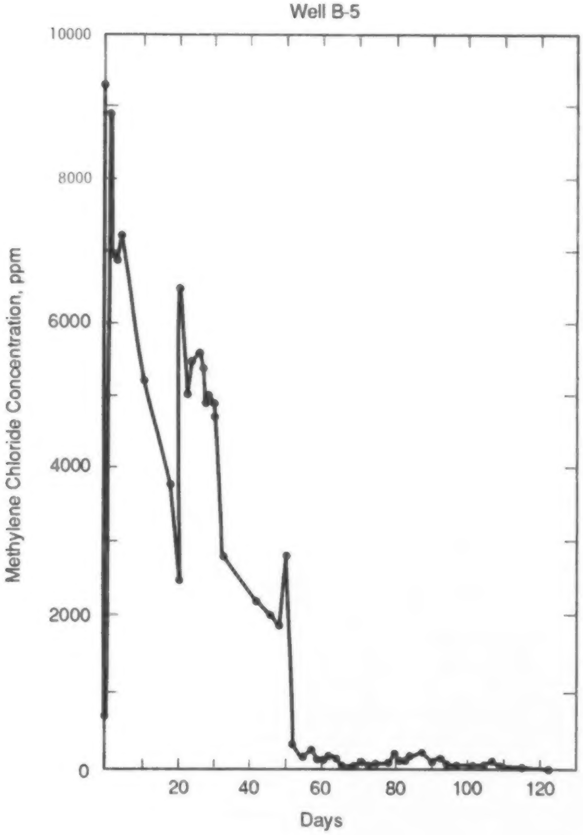
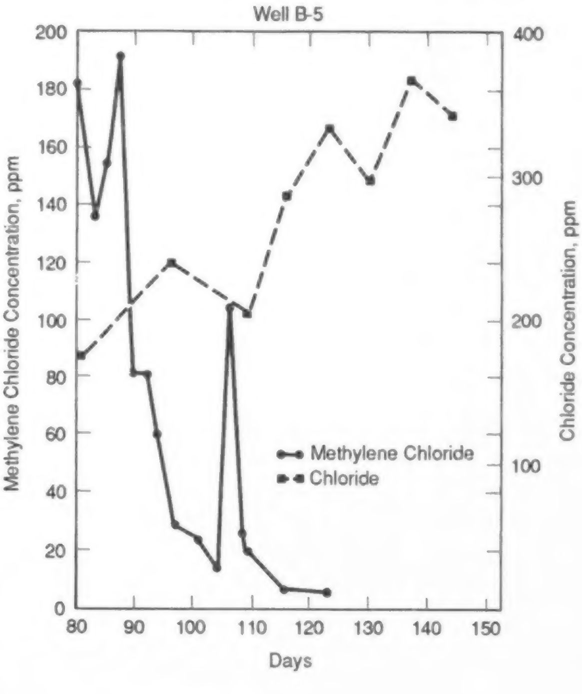


Figure A-18. Reduction in methylene chloride concentration in well B-5 achieved during biodegradation (Flathman and Caplan 1986).



A.8.7 References

Flathman, P. E., and J. A. Caplan. 1986. Cleanup of Contaminated Soil and Ground Water Using Biological Techniques. In: Proceedings of the National Conference on Hazardous Wastes and Hazardous Materials, March 4-6, 1986. Hazardous Materials Control Research Institute, Silver Spring, Maryland.

Flathman, P. E., et al. 1985. In Situ Physical/Biological Treatment of Methylene Chloride (Dichloromethane) Contaminated Ground Water. In: Proceedings of the Fifth National Symposium on Aquifer Restoration and Ground Water Monitoring, Columbus, Ohio, May 1985.

A.9 Case History I–Biocraft Laboratories, Waldwick, New Jersey

A.9.1 Background

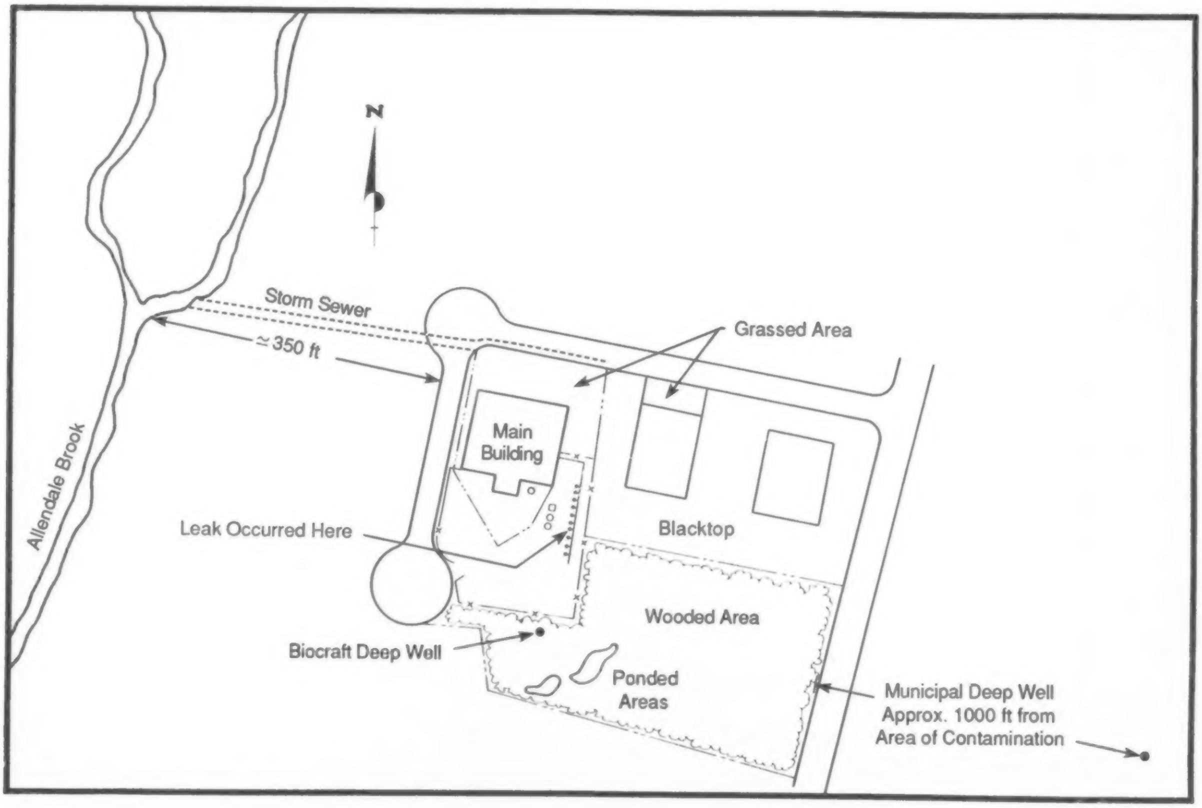
Biocraft Laboratories is a small synthetic-penicillin manufacturing plant located on a 4.3-acre site in an industrial park in Waldwick, New Jersey. In August 1975, environmental degradation was observed in Allendale Brook and its tributary, a small creek 350 feet east of the site. The source of contamination in these streams was traced to a storm-sewer line that runs across the Biocraft plant site and discharges into the creek. Subsequent investigations by Biocraft revealed that two pipes leading from the plant to underground waste-solvent storage tanks were leaking and that a mixture of solvents had infiltrated the storm-sewer line.

A.9.2 Site Description

The Biocraft Laboratories plant site is in the northern section of Bergen County, New Jersey. The property is relatively flat (0 to 3 percent slope). Approximately 30 percent of the area is paved or covered with buildings, 10 percent is grassed, and the remaining 60 percent is lightly forested (Figure A-19).

Glacial till, composed of a poorly sorted mixture of boulders, cobbles, pebbles, sand, silt, and clay, underlies the surface at a thickness of 8 to 15 feet. Permeability varies throughout the till layer and ranges from 0.02 to 36 gal/day per ft^2 (EPA 1984; Jhaveri and Mazzacca 1983).

Figure A-19. **Biocraft Laboratories site, Waldwick, New Jersey (Jhaveri and Mazzacca 1985).**



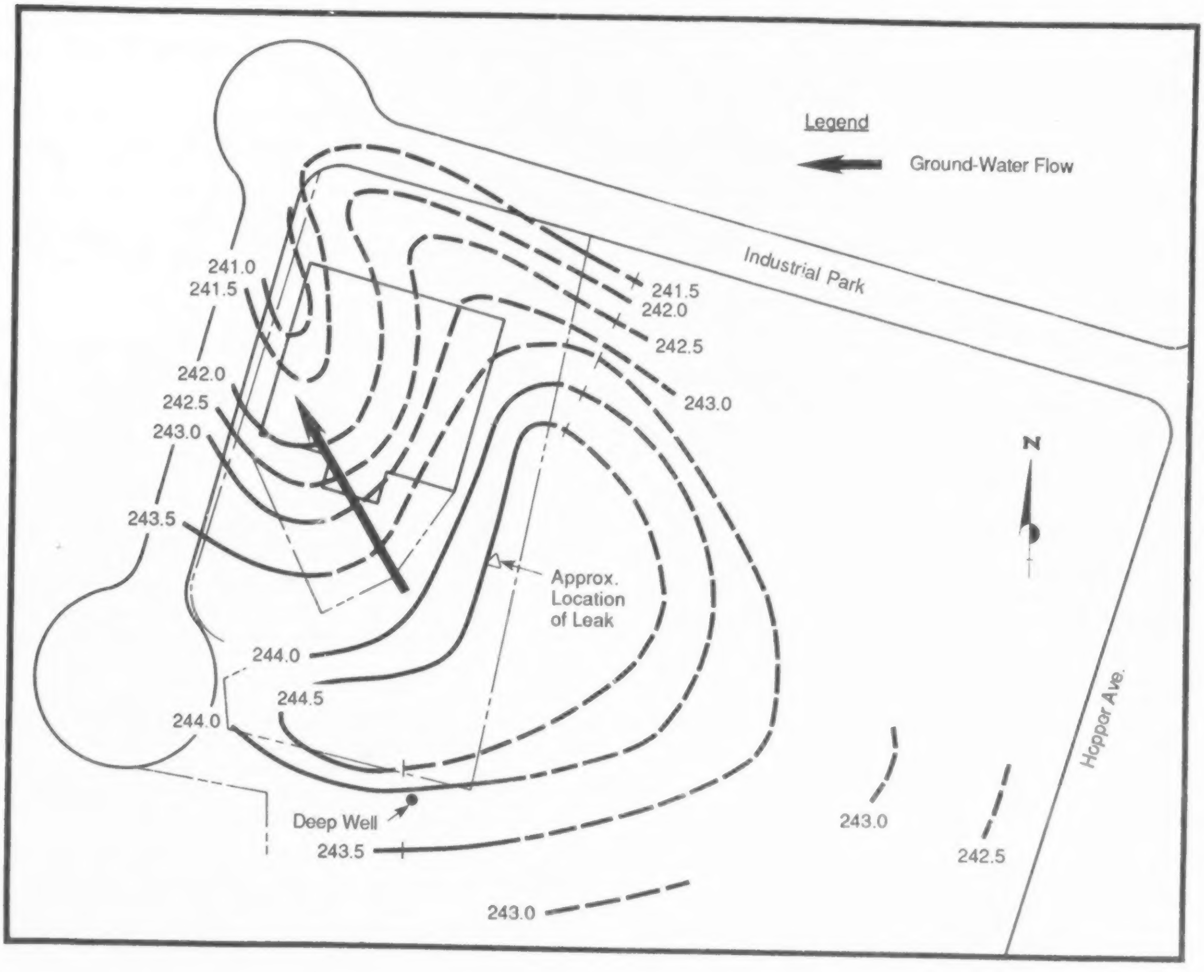
Approximately 40 feet of semiconsolidated silt and fine sand underlie the till layer. Although no testing has been conducted, visual inspection of this material suggests it has a very low permeability and functions as an aquiclude (EPA 1984; Jhaveri and Mazzacca 1983).

Brunswick shale underlies the semiconsolidated layer at a depth of 50 to 60 feet and a thickness of several hundred feet. The Brunswick formation is the primary water-supply aquifer for the area. Primary ground-water flow occurs in the interconnecting fractures, vertical joints, and faults in the shale, whereas little or no flow occurs in the rock. A municipal deep well is located in the Brunswick formation approximately 1000 feet east of the spill site. Biocraft Laboratories' own deep well, which supplies water for their chemical manufacturing operations, is located directly under the contaminant plume.

As shown by the ground-water surface contours in Figure A-20, ground-water flow at the Biocraft site is somewhat irregular because of the heterogeneous geology, diverse surface cover, and other factors. A noticeable ground-water mound, corresponding to the south and east edges of the blacktopped area, is present; this represents an area of ground-water recharge. Ground-water flow from the mound is omnidirectional, but the major flow regimes move toward the northwest, northeast, and south.

The average depth to ground water ranges from 0 to 9 feet, depending on seasonal fluctuations. Ground-

Figure A-20. **Ground-water surface contours (Jhaveri and Mazzacca 1983).**



water flow in the shallow aquifer is fairly rapid (average rate is 0.4 ft/day) (EPA 1984; Jhaveri and Mazzacca 1983).

A.9.3 Nature and Extent of Contamination

Sometime between June 1972, when the plant opened, and August 1975, when the contamination was discovered, two pipes feeding underground waste-solvent storage tanks began leaking a mixture of methylene chloride, acetone, n-butyl alcohol, and dimethyl aniline. Based on daily tank inventory readings, Biocraft estimated that as much as 33,000 gallons (285,000 pounds) of waste solvents, as identified in Table A-1, may have leaked into the subsurface (EPA 1984; Jhaveri and Mazzacca 1983).

Table A-1. Estimated Quantities of Solvents Released*

Substance	Estimated Quantity (lb)
Methylene Chloride	181,500
n-Butyl Alcohol	66,825
Dimethyl Aniline	26,300
Acetone	10,890
Total Solvents	285,515

* Data are from EPA 1984 and Jhaveri and Mazzacca 1983.

Contamination was confined to the shallow aquifer. The contaminant plume flowed predominantly north and northeast (toward the northern edge of the property and a storm sewer) and south (toward the southern property boundary). The contaminated area covered approximately 1.75 acres and encompassed 12,000 yd^3 of soil (Amdurer, Fellman, and Abdelhamid 1985; Jhaveri and Mazzacca 1983).

A.9.4 Corrective Action

The leaking underground feed lines to the storage tanks were sealed in the winter of 1975, and above-ground feed lines were installed. During January 1976, six ground-water monitoring wells (2-inch well points with depths ranging from 10 to 15 feet) were constructed on site. From June 1976 to early 1979, 16 additional wells were installed for monitoring and pumping contaminated ground water. Figure A-21 shows the locations of these wells.

From January 1977 through 1978, five wells (Nos. 2, 3, 8, 10, and 13) were selectively pumped at a combined rate of 10,000 gal/min, and the contaminated ground water was disposed of offsite (at an industrial wastewater plant, an incinerator, or a pretreatment facility) at an average cost of $0.35/gal (Amdurer, Fellman, and Abdelhamid 1985; Jhaveri and Mazzacca 1983).

In December 1978, dissatisfied with the progress of these initial measures to clean up the contaminated ground water, the State ordered Biocraft to accelerate the decontamination process. Several alternative response technologies were considered, including the following:

- Collecting and treating all discharge from the storm sewer.
- Isolating the storm sewer from the contaminated flow by resleeving the existing pipe, grouting the pipe joints, or replacing the sewer with a noninfiltrating pipe.
- Surrounding the contaminated area with grout or a slurry cutoff wall and pumping and treating or disposing of the ground water from within the confined area.
- Excavating the entire contaminated soil column under the site.

Each of these alternatives was rejected, in turn, as ineffective, impractical, or too costly.

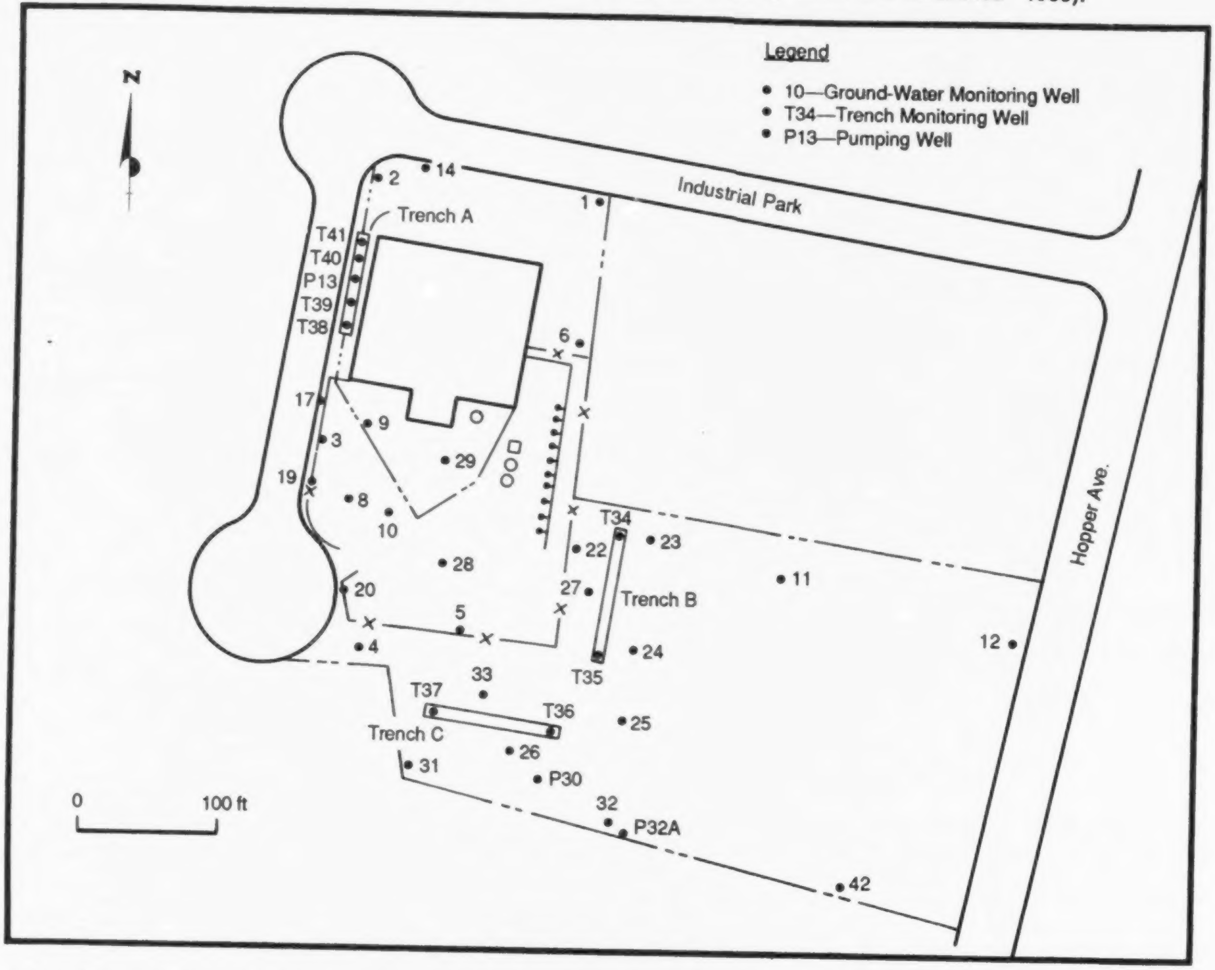
In May 1979, Biocraft Laboratories and the State settled on a biodegradation-biostimulation process designed to provide both contaminant plume containment and removal of the source of contamination in a cost-effective manner. The system, which has been patented by Groundwater Decontamination Systems, a subsidiary of Biocraft Laboratories, entails the following:

- Collecting the contaminated plume downgradient of the source area in a slotted-pipe collection trench and two interceptor wells.
- Treating the collected ground water in a surface aerobic biological treatment system.
- Injecting the treated "bioactive" water upgradient of the source area in two slotted-pipe recharge trenches to flush the soil of contaminants.
- Stimulating in situ biodegradation of contaminants in the subsurface by injecting air through a series of aeration wells along the path of ground-water flow.

It was estimated that this system would require 5 years for complete restoration of the Biocraft site compared with an estimated 15 to 20 years for the initial ground-water withdrawl and offsite disposal alternative (Amdurer, Fellman, and Abdelhamid 1985).

The research and development phase of the project, which spanned 2-1/2 years, included a hydrogeolic investigation, bench- and pilot-scale studies, and design and construction of system components. Installation of the system was completed in June 1981. Major system components include a

Figure A-21. Location of ground-water monitoring and pumping wells (Jhaveri and Mazzacca 1985).


Legend
● 10—Ground-Water Monitoring Well
● T34—Trench Monitoring Well
● P13—Pumping Well
N
Industrial Park
Hopper Ave.
Trench A
Trench B
Trench C
T41
T40
P13
T39
T38
T34
T35
T36
T37
P30
P32A
1
2
3
4
5
6
8
9
10
11
12
14
17
19
20
22
23
24
25
26
27
28
29
31
32
33
42
0
100 ft

subsurface collection drain (Trench A), two interceptor wells, a four-tank dual biological treatment system, two effluent injection trenches (Trenches B and C), and a series of nine in situ aeration wells (see Figures A-22 and A-23).

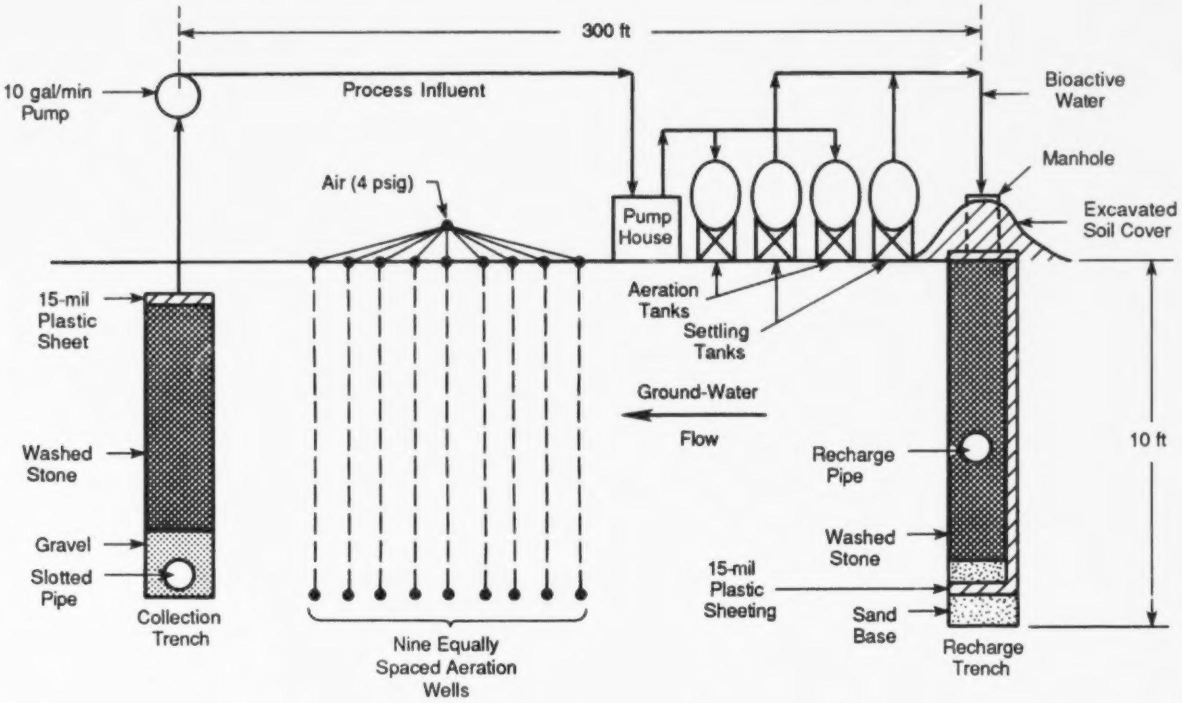
The primary ground-water collection system consists of a subsurface drain about 80 feet long, 4 feet wide, and 10 feet deep. Two 16-inch slotted steel collection pipes were laid on a bed of gravel at the bottom of the trench, sloped toward the center, and connected to a central collection pumping well. This well (No. 13) has a 12-inch-diameter steel casing with a 2.5-foot slotted screen and a 10 gal/min stainless steel submersible pump. The trench has two 2-inch-diameter PVC monitoring wells installed on each side of the central collection well. The trench was backfilled with washed stone and then covered with 15-mil plastic sheet, backfilled with earth, and finished to grade.

Ground-water pumping is also being carried out in two interceptor wells (Nos. 30 and 32A) on the southern edge of the property to collect the southern component of the contaminant plume. These wells consist of trenches about 16 feet long, 4 feet wide, and 10 feet deep. An 8-inch and a 12-inch PVC fully slotted casing and 10 gal/min submersible pump were installed in well Nos. 30 and 32A, respectively. The trenches were then backfilled with washed stone and earth and finished to grade.

An average of 13,680 gal/day of water is pumped from the collection trench and the interceptor wells to the biological treatment system. This system consists of four tanks (two aeration tanks and two sludge settling tanks), each with a capacity of about 5400 gallons.

Influent water from the collection trench and two interceptor wells is pumped first to the aeration tanks, where most of the biodegradation occurs. The

Figure A-22. Cross section of biodegradation-biostimulation system (EPA 1984).


300 ft
10 gal/min Pump
Process Influent
Bioactive Water
Manhole
Air (4 psig)
Pump House
Excavated Soil Cover
15-mil Plastic Sheet
Aeration Tanks
Settling Tanks
Ground-Water Flow
Washed Stone
Recharge Pipe
10 ft
Gravel
Slotted Pipe
Collection Trench
Washed Stone
15-mil Plastic Sheeting
Sand Base
Recharge Trench
Nine Equally Spaced Aeration Wells

microorganisms isolated from the aeration tanks consist of *Pseudomonas* (40 percent), *Agrobacterium* (40 percent), and *Arthrobacter* (20 percent), which are naturally occurring soil bacteria (Jhaveri and Mazzacca 1983). Air is added to each tank through a series of porous ceramic tube diffusers at a rate of 20 ft³/min. Temperature is kept constant at 68°F by single-pass steam coils installed in the tanks. The tanks have 2 inches of insulation to help buffer the effects of ambient temperature. A nutrient solution is metered in from mixing tanks in the pump house to obtain the following concentrations in the aeration tanks:

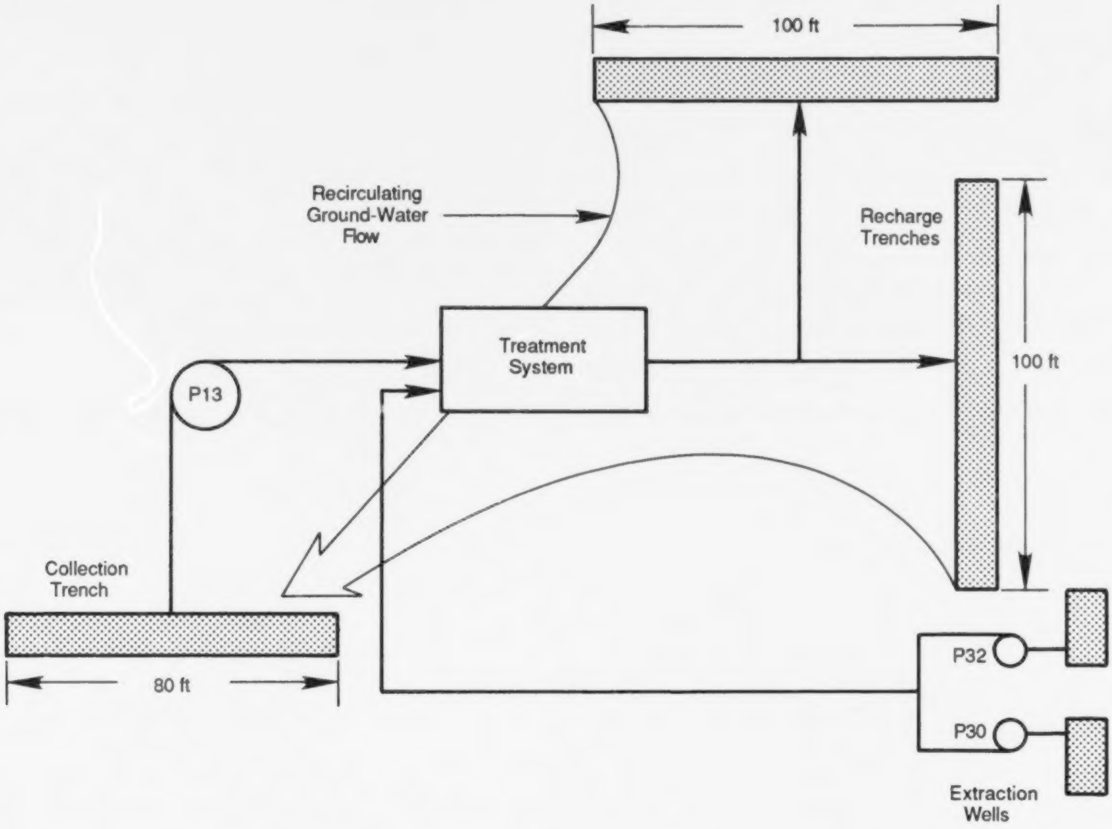
Nutrient salt	Concentration, mg/liter
NH_3Cl_2	500
KH_2PO_4	270
K_2HPO_4	410
$MgSO_4$	14
Na_2SO_4	9
$CaCl_2$	0.9
$MnSO_4$	1.8
$FeSO_4$	0.45

The system now operates at an average flow rate of 9.5 gal/min or 13,500 gal/day; retention time in the aeration tanks is 17.5 hours. The system can handle a flow of up to 14 gal/min or 20,000 gal/day with a retention time of 12 hours, but the pumping wells are already at capacity flow.

Effluent air from the aeration tanks passes through vapor-phase carbon adsorbers to remove any volatilized organics. Pilot-plant studies and the infrequent need for replacement carbon indicate that the amount of volatilization is not substantial.

The effluent streams from the aeration tanks are combined and pumped to two sludge settling tanks, where some biomass solids are settled out and recycled to the aeration tanks (approximately 200

Figure A-23. **Plan view of biodegradation-biostimulation system (EPA 1984).**



gal/day). Much of the biomass, however, is allowed to pass with the supernatant into the recharge trenches to provide continuous inoculation of the subsurface with microorganisms. Waste sludge production is minimal (approximately 11 gal/min) because sludge is recycled to the aeration tanks and reinjection trenches and cell reproduction rates associated with the biodegradation of relatively refractory organics are low.

Effluent from the biological treatment plant is reinjected through two recharge trenches located at the ground-water mound to flush the soil and subsurface with treated water to remove residual contaminants. The dimensions of each trench are approximately 100 feet long, 4 feet wide, and 10 feet deep. The trenches are lined on the bottom, ends, back, and top with a 15-mil plastic liner so that injected water can exit only from the front side of the trench. The bottom section of the liner was laid on 1 foot of sand and then covered with 0.5 foot of sand. The trenches were filled with 2-inch washed stone to a thickness of 5 feet. A 2-inch vertical inlet pipe ending in a "Y" connection was installed in the center of the trench. Connected to the "Y" were two 20-foot sections of 2-inch slotted pipe. The trench was then backfilled to the surface with 2-inch washed stone. A 4-foot-high manhole was installed over the recharge pipe for access. A 4-foot-high soil mound was then placed over the top liner to insulate the trench from freezing. Each trench has two monitoring wells, one at either end of the trench. These wells can also be used for flushing the system of sludge accumulation if required. Average flow of effluent to the two trenches is about 13,680 gal/day.

As effluent flows from the treatment plant to the trenches, air is injected into the recharge line with a jet ejector or air compressor when the flow rate is low. Aeration of the reinjected effluent creates a biological trickling filter in the trenches, which further increases biodegradation of organics. The water level in the trenches is kept at surface elevation to flush contaminants in the shallow soil layers.

A series of nine continuous aeration wells were installed in the subsurface along the major path of contaminant plume movement. Air is injected into each well at a pressure of 4 to 9 lb/in.[2] Adding air to these wells creates a zone of subsurface aeration, where contaminants in the groundwater passing near the wells are aerobically biodegraded. The nine wells are spaced on 30-foot centers and arranged in a rectangular matrix about 30 feet wide and 100 feet long. The arrangement of the wells was based on an assumed 15-foot radius of influence. Residence time through the aeration zone, assuming an average ground-water velocity of 0.4 ft/day, ranges from 65 to 300 days, depending on the direction of ground-water flow. Ground-water temperature averages 54°F, which is adequate for biodegradation.

The nutrient tanks, pumps, flow meters, temperature recorders, etc., are housed in a small control room. Monitoring and rate adjustments are performed as required.

A.9.5 Performance Evaluation

After 3 years of operation, the contaminant plume was reportedly reduced by 90 percent (Figure A-24) (Jhaveri and Mazzacca 1985). The reduction of COD in monitoring wells No. 3 and No. 10, which were highly contaminated prior to the biostimulation process, is shown graphically in Figures A-25 and A-26. Continuous core samples taken in the vicinity of these wells show no detectable contamination from 0 to 12 feet at a detection limit of 0.8 mg/liter (Jhaveri and Mazzacca 1985).

Figure A-24. Reduction of contaminant plume (Jhaveri and Mazzacca 1985).

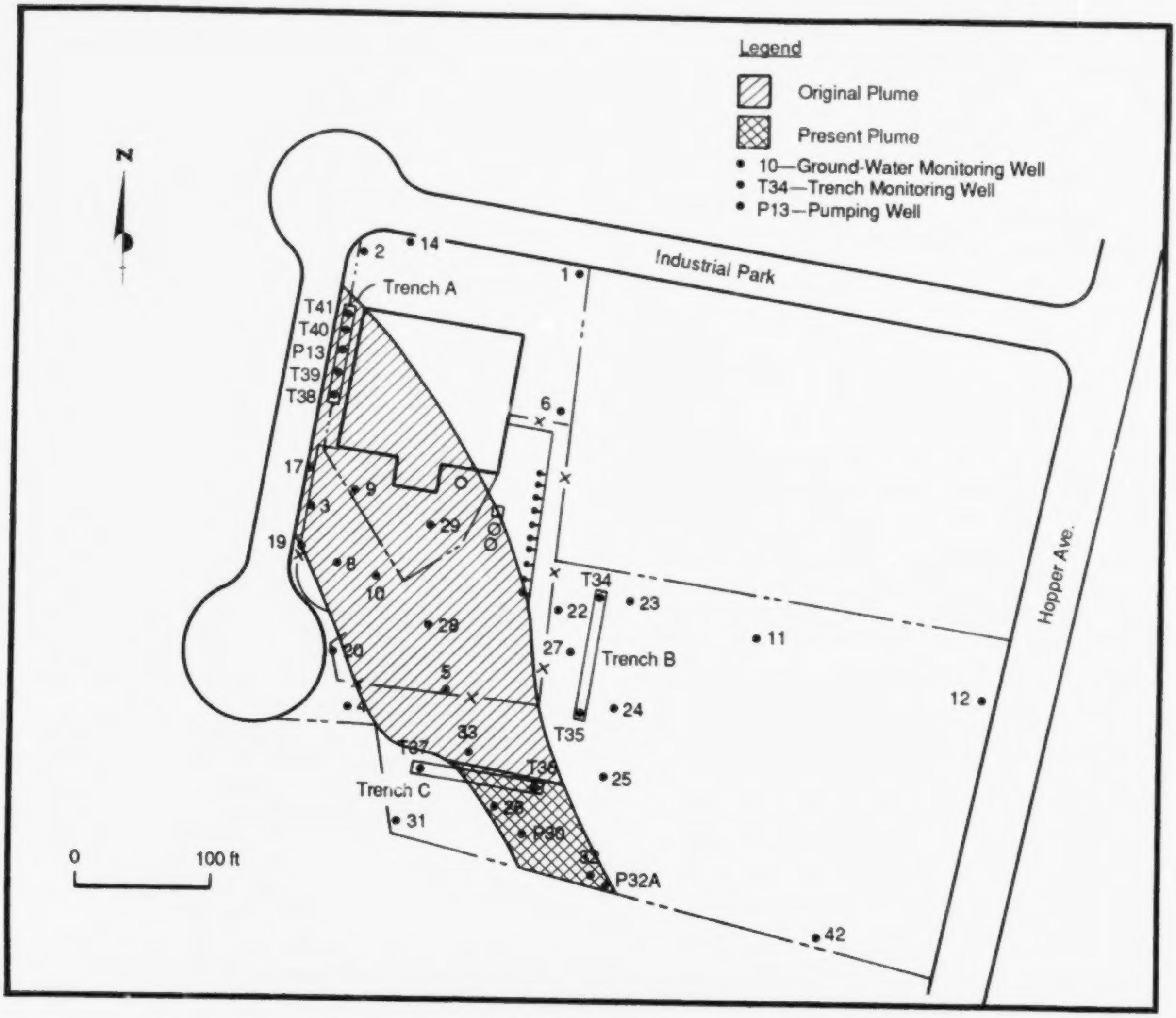
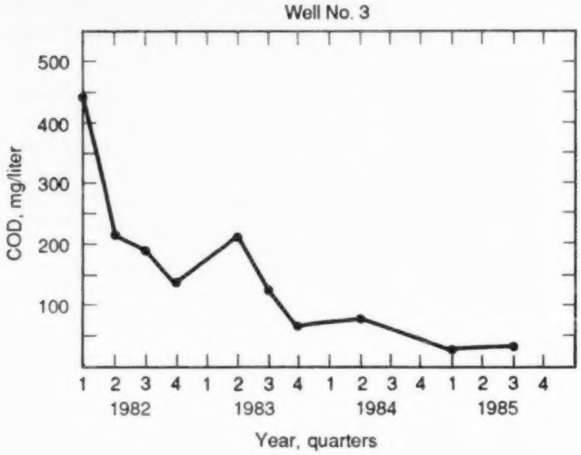

Legend
▨ Original Plume
▩ Present Plume
• 10—Ground-Water Monitoring Well
• T34—Trench Monitoring Well
• P13—Pumping Well
N
Industrial Park
Hopper Ave.
Trench A
Trench B
Trench C
T41
T40
P13
T39
T38
T34
T35
T36
T37
P30
P32A
1
2
3
4
5
6
8
9
10
11
12
14
17
19
20
22
23
24
25
26
27
29
31
33
42
0
100 ft

Figure A-25. **Reduction of COD in well No. 3 (Jhaveri and Mazzacca 1985).**



The area near the pumping wells on the southern edge of the plume, which shows the highest level of residual contamination, is still biologically active. This is evident from increased concentrations of dissolved CO_2 (a byproduct of aerobic respiration) in monitoring wells in that zone (Jhaveri and Mazzacca 1985).

A.9.6 Project Costs

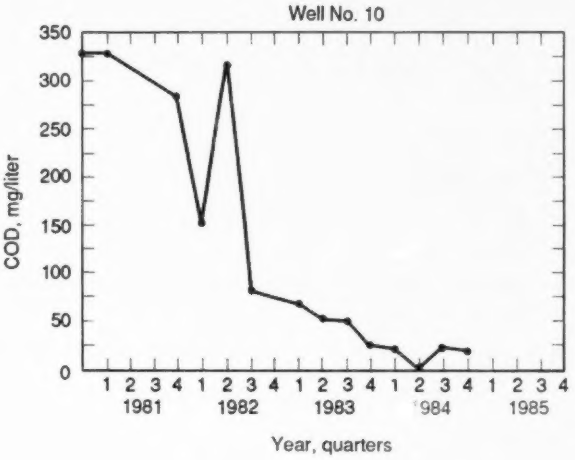
The total cost of research and development (R&D) and capital design and construction of the biostimulation operation at Biocraft was about $926,000 (EPA 1984). These costs are reported in Table A-2. About half of the total capital cost ($446,280) was for in-house process development, including construction of a pilot plant. Virtually all of this process development cost was a one-time-only expense.

Table A-2. **Capital Costs, Biocraft Laboratories***

Activity	Cost ($)
Hydrogeological study	73,948
Research and development	446,280
Ground-water collection/recharge system design and installation	184,243
Biological treatment plant design and construction	221,207
Total capital costs	925,678

* Data from EPA 1984.

Figure A-26. **Reduction of COD in well No. 10 (Jhaveri and Mazzacca 1985).**



The operation and maintenance (O&M) costs (reported in Table A-3) include utilities, maintenance labor and overhead, and chemicals. Total O&M costs are approximately $226.53/day (EPA 1984). At an average daily treatment rate of 13,680 gal/day, unit O&M costs are about $0.0165/gal.

Table A-3. **Operation and Maintenance Costs, Biocraft Laboratories***

Component	Cost Per Day ($)
Utilities (steam, electricity)	47.40
Maintenance	159.93
Nutrients	19.20
Total O&M costs	226.53

* Data from EPA 1984.

Total capital and O&M costs of the biodegradation-biostimulation process now in operation at the Biocraft site are estimated to be a quarter of the total cost that would have been incurred with the initial remedial measure (i.e., pumping and offsite disposal) (Amdurer, Fellman, and Abdelhamid 1985).

A.9.7 References

Amdurer, M., R. Fellman, and S. Abdelhamid. 1985. In Situ Treatment Technologies and Superfund. In: Proceedings of International Conference on New Frontiers for Hazardous Waste Management. EPA-600/9-85-025.

Jhaveri, V., and A. J. Mazzacca. 1983. Bioreclamation of Ground and Ground-water, Case History. In: National Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, D.C., October 31-November 2, 1983. Hazardous Materials Control Research Institute, Silver Spring, Maryland.

Jhaveri, V., and A. J. Mazzacca. 1985. Bioreclamation of Ground and Ground-water by In Situ Biodegradation: Case History. In: The Sixth Annual National Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, D.C., November 4-6, 1985. Hazardous Materials Control Research Institute, Silver Spring, Maryland.

U.S. Environmental Protection Agency. 1984. Case Studies No. 1-23: Remedial Response at Hazardous Waste Sites. EPA-540/2-84-002b.

A.10 Case History J–Fairchild Camera and Instrument Corp., South San Jose, California

A.10.1 Background

On December 4, 1981, Fairchild Camera and Instrument Corp. of South San Jose, California, a manufacturer of semiconductor devices, reported a leak in excess of 20,000 gallons from an underground waste solvent storage tank to the California Regional Water Quality Control Board (San Francisco Bay Region). Fairchild's subsequent analysis of inventory records revealed an estimated chemical loss of 43,000 gallons over an 18-month period (June 1980 through November 1981). The leak was apparently caused by chemical degradation of the fiberglass tank, which contained a mixture of 1,1,1-trichloroethane (TCA), xylene, acetone, and isopropyl alcohol (IPA). According to company records, the mixture contained approximately 15 percent TCA.

A.10.2 Site Description

The Fairchild plant site is located on the Santa Teresa Plain in the southern Santa Clara Valley ("Silicon Valley") of California. The main plant is approximately a half-mile west of the Santa Clara Valley Water District's Coyote Percolation Pond, which is used to recharge the area's ground-water aquifers. The ground water flows from the percolation pond toward the Fairchild facility and is extracted by the Great Oaks Water Company at numerous wells downgradient.

The Fairchild site is underlain by two distinct alluvial deposits separated by a buried, clayey-silt-filled valley known as Edenvale Gap, which generally trends east to west. The alluvial deposits on either side of the gap consist of interlayed strata of sands, gravels, silts, and clays. Many strata are discontinuous and may be locally interrupted by buried stream channels. The coarser-grained strata (sands and gravels) compose an aquifer system under the plant. The less permeable strata (silts and clays) tend to retard, but not prevent, movement of water and contaminants between aquifers.

Four aquifers, designated A, B, C, and D, have been identified beneath the Fairchild site. The A aquifer, which is transected by Edenvale Gap, generally occurs in the upper 50 feet of the alluvium. It is first encountered 10 to 20 feet below the ground surface north of the gap (east of the plant) and 35 to 40 feet below the ground surface south of the gap (west of the plant). These two shallow aquifers are hydraulically connected in the vicinity of the leaking tank.

The B aquifer occurs at a depth of 60 to 100 feet and is laterally continuous across the plant site. The A-B aquitard, which ranges in thickness from 5 to 30 feet, separates the shallow A aquifers from the deeper B aquifer. The A and B aquifers appear to merge and form a single A/B aquifer at a point a few hundred feet west of the main plant.

The C aquifer occurs from 150 to 190 feet below the ground surface and the D aquifer occurs from 220 to 270 feet below grade. (The D aquifer is poorly defined and nonexistent in some areas.)

Ground-water flow in the shallow aquifers has both a horizontal and a vertical component. The horizontal component is generally northwest toward Edenvale Gap and through the narrow hydraulic connection between the A aquifers. The vertical component of ground-water flow has resulted in downward migration of contaminated ground water into deeper aquifers. Pathways for this vertical migration are believed to be:

- Through sand interbeds in the A-B aquitard.
- By slow seepage through fine-grained strata separating aquifers.
- Through improperly cased or abandoned wells that penetrate multiple aquifers.

A.10.3 Nature and Extent of Contamination

At the direction of the California Regional Water Quality Control Board (RWQCB), the lead agency involved in this incident, Fairchild conducted detailed subsurface geologic and hydrogeologic investigations to define the extent of soil and ground-water contamination. Numerous soil borings and ground-water monitoring wells were drilled both on site and offsite over a period of several months following discovery of the waste solvent leak.

Results of the soil exploration program showed concentrations of solvents in the soil on site extending to a depth of 50 feet (i.e., to the A-B aquitard). Solvents were concentrated in the area immediately adjacent to the waste solvent tank (personal communication regarding proposed Fairchild's conceptual onsite remedial plan from P. E. Antommaria, Canonie Environmental, Chesterton, Indiana, to L. Amon, Manager, Real Estate and Facilities Planning, Fairchild Camera and Instrument Corp., Mountain View, California, July 26, 1982).

Results of the ground-water monitoring program revealed a plume of contamination roughly 2000 feet long and 1000 feet wide that extended west from the Fairchild facility to the Great Oaks Water Company well No. 13 [GO-13(M)] (internal memo regarding underground waste solvent leak at Fairchild Camera and Instrument Corp. from P. W. Johnson and H. J. Singer, Toxics Division, to F. H. Dierker, Executive Officer, California Regional Water Quality Control Board, San Francisco Bay Region, March 8, 1982). The most extensive TCA contamination was found in the B aquifer. Initially, TCA was detected in GO-13 at levels up to 5.7 ppm; however, no other municipal wells in the vicinity appeared to be affected (Levine 1981).

A.10.4 Corrective Action

Upon discovery and reporting of the waste solvent leak, Fairchild immediately emptied the underground tank and replaced it with a temporary aboveground tank. The underground tank and the highly contaminated soils adjacent to it were subsequently excavated.

On January 19, 1982, Fairchild began extracting ground water from G0-13 to create a zone of influence that would draw the contaminant plume into the well and prevent its migration further downgradient. The extracted ground water was treated by three-stage carbon adsorption before being discharged via a storm sewer to Canoas Creek, a tributary of the Guadalupe River. This discharge was permitted under NPDES. Initially, G0-13 was pumped at a rate of 500 gal/min; production was more than tripled over the next 6 months as additional treatment capacity was added.

A.10.4.1 Onsite Remedial Activities

A plan outlining Fairchild's proposed onsite remedial activities was submitted to the RWQCB on July 26, 1982. This plan, which was envisioned to minimize the potential for migration of materials from the site and to restore ground water beneath the site, called for:

- Excavation of solvent-contaminated soils to the extent practicable in the area adjacent to the former waste solvent tank.
- Installation of a purge well in the vicinity of WCC-14(B), where the A and B aquifers merge.
- Treatment of the purged ground water.
- Continued monitoring of the site.

Data from the soil exploration program showed concentrations of solvents in the soil to a depth of 50 feet in the area immediately adjacent to the tank. Because of the proximity of this area to the plant and the depth of solvent concentration, it was originally believed that soil removal from the site would be technically and economically infeasible. Further study of the problem, however, yielded a method for soil removal based on a modified caisson installation technique.

Excavation of highly contaminated soils began in October 1982. As soil was removed from the caissons, they were filled with concrete. Ground water encountered during the excavation was pumped through the onsite carbon treatment system and discharged to Canoas Creek. Approximately 3000 yd^3 of soil were removed from the site in covered, watertight trucks and disposed of at sites approved by the California Department of Health Services (internal memo of October 12, 1983, from P. W. Johnson, Toxics Division, to F. H. Dierker, Executive Officer, California Regional Water Quality Control Board, San Francisco Bay Region, in response to Dr. D. Todd's memo of September 19, 1983, to B. Roeder). Soil removal was important to the reduction of the quantity of chemicals that were subsequently removed by ground-water purging.

On November 5, 1982, following completion of the soil excavation phase of remediation, Fairchild obtained written approval from the RWQCB to implement a ground-water extraction/treatment program designed to intercept the contaminant plume closer to the source and thereby minimize the offsite migration of solvents. A newly installed purge well, RW-1(A,B), and an existing 8-inch observation well, WCC-20(B), which were located in the main pollutant plume near the plant, were pumped at a combined flow rate of 1200 gal/min. The extracted ground water from RW-1 and WCC-20 was treated by carbon adsorption* prior to its discharge to a storm drain tributary of Canoas Creek. Effluent limits for the combined discharge from RW-1, WCC-20, and G0-13 as set forth in RWQCB Order No. 82-61 are presented in Table A-4. In addition, the Bay Area Air Quality Management District limited air emissions at the point of discharge to 150 lb/day of smog precursors (all constituents except TCA) and 150 lb/day of nonsmog precursors (TCA) (personal communication regarding Fairchild's extraction, treatment, and discharge of contaminated ground water from F. H. Dierker, Executive Officer, California Regional Water Quality Control Board, San Francisco Bay Region, to L. Amon, Fairchild Camera and Instrument Corp., Mountain View, California, November 5, 1982).

---

*Other treatment options investigated included air stripping and oxidation by ozone or peroxide; however, these technologies failed to achieve the specified effluent and air emission limitations.

Table A-4. Extracted Ground-Water Effluent Limitations*

Constituent	Effluent Limit (daily maximum) (mg/liter)
Acetone	50
1,1-Dichloroethylene	0.30
Isopropyl alcohol	50
Sum of monocyclic compounds (includes 1,2-dichlorobenzene, ethylbenzene, toluene, xylene)	0.10†
1,1,1-Trichloroethane	5.00
Tetrachloroethylene	0.10

* Data from CRWQCB (undated).

† The discharge may contain monocyclic compounds in excess of the 0.1 mg/liter daily maximum, but not to exceed1.0 mg/liter, up to 4 days per month.

Throughout the period of onsite remedial activities, work areas were monitored for organic vapors with organic vapor analyzers (OVA's), water levels in onsite observation wells were recorded to determine field drawdowns, and ground-water samples were collected for routine chemical analysis.

A.10.4.2 Offsite Remedial Activities

In March 1982, contamination appeared in well 17N1(M), which indicated that pumping of G0-13 was not effectively containing the solvent plume (personal communication from B. B. Roeder, President, Great Oaks Water Company, to J. S. Vigil, Redevelopment Agency, City of San Jose, California, July 16, 1982). Concern that further spread of the plume could contaminate downgradient municipal water supply wells was addressed by the development of an offsite groundwater extraction system. The system consisted of redundant purge capabilities at four locations between the Fairchild facility and GO-4(M).

The first line of extraction wells was in the vicinity of GO-13 and included existing wells 17N1 and 17N11(M) plus newly constructed wells in the B and C aquifers [RW-2(B) and RW-3(C)]. Because the TCA concentrations measured at these wells were well below the established discharge limits, treatment of the purged water was not required.

The second line of extraction wells was located approximately 500 feet downgradient of GO-13 along San Ignacio Avenue between Via del Oro and Santa Teresa Boulevard. Pumping wells in this location included WCC-18(C) and RW-12(B).

The third line of extraction wells, which included WCC-32(C) and RW-14(B), was located approximately 2200 feet downgradient of GO-13. The fourth and final extraction capability was a single well, RW-13(B), located approximately 500 feet upgradient of GO-4.

Pumping capacity of the offsite purge system totaled 5200 gal/min. Individual wells were selectively pumped in an effort to control the migration of the contaminant plume.

A.10.4.3 Shallow Aquifer Flushing

To accelerate the removal of solvents from the shallow A aquifer and to reduce the need for offsite ground-water recovery, Fairchild implemented a shallow aquifer flushing program at the San Jose plant site. The program, which ran from March 8, 1984, to December 31, 1984, involved the injection of clean water into three shallow A aquifer wells near the main plant building and recovery of the recharge water at several downgradient A and B aquifer extraction wells. Flushing of solvents from the soil was achieved by the movement of the water through the A and B aquifers.

Treated ground water from extraction wells RW-1, RW-25(B), WCC-1(B), and WCC-2(B) was injected into Wells WCC-41(A), RW-15(A), and RW-16(A) to recharge the shallow aquifer. The injected water was treated either by carbon adsorption or by air stripping. The recharged ground water created an artificial hydraulic mound around the recharge wells. As the recharge water flowed away from the mound, it transported solvents through the soil to the recovery wells. Most of the recharge water was recovered from the B aquifer.

The shallow aquifer flushing program operated for 10 months, during which time solvent concentrations in both the A and B aquifers were significantly reduced (Canonie Engineers 1985). The flow path of the recharging water, however, proved to be difficult to control because of the irregular bottom topography of the A aquifer, and the operation was suspended.

A.10.4.4 Slurry Wall

Despite continued purge pumping of the A and B aquifers and attempts to flush contaminants from the soil, solvent concentrations in the ground water on site remained high. Purging operations had dewatered the A aquifer and had significantly lowered the water table level in the B aquifer. Residual contaminants trapped in the unsaturated soil were gradually leaching into the ground water.

To address this continuing source of ground-water contamination, Fairchild constructed a 3500-foot-long perimeter slurry wall in the fall/winter of 1985 for complete enclosure and isolation of the 15-acre site. The wall, which was constructed of a 3 percent soil-bentonite slurry, extends completely below the A and B aquifers and ranges in depth from 70 to 140 feet. The 3-foot-wide barrier has a very low permeability (approximately 10^{-7} cm/s) and is keyed into the clay aquitard beneath the B aquifer. Ground-water pumping is maintained at a rate sufficient to establish an inward pressure gradient.

Offsite plume management is continuing via pumping of the B and C aquifers. Several options are being considered as final remedial measures within the walled area. These options include resaturation/ground-water purging, air purging, in situ biodegradation, and no action. In the interim, however, the slurry wall will function as a hydraulic barrier to prevent the continued migration of pollutants offsite.

A.10.5 Performance Evaluation

The status of onsite and offsite remedial efforts is documented each month in progress reports to Fairchild prepared by their technical consultants. The soil excavation operation in October 1982 substantially reduced the amount of TCA in the onsite soils; approximately 3000 yd^3 of soil containing TCA in excess of 100 ppm was removed. By October 1983, TCA concentrations in the A and B aquifers near the source area had been reduced an average of 88 percent and 95 percent, respectively. Solvent concentrations at offsite locations also have been substantially reduced (internal memo of October 12, 1983, from P. W. Johnson, Toxics Division, to F. H. Dierker, Executive Officer, California Regional Water Quality Control Board, San Francisco Bay Region, in response to Dr. D. Todd's September 19, 1983, memo to B. Roeder). Although decontamination of the Fairchild site is proceeding effectively, complete onsite and offsite remediation may be several years away.

A.10.6 Project Costs

Costs to date for remedial activities at the site, including removal of the tank and the soil beneath it, installation of onsite and offsite extraction wells, and construction of the slurry wall, exceed $23 million (CRWQCB 1985; internal memo to file regarding Fairchild Camera and Instrument Corp.'s proposed slurry wall from M. Kurtovich, Associate Engineer, California Regional Water Quality Control Board, San Francisco Bay Region, July 17, 1985). Because final cleanup levels have not yet been established, total project costs cannot be estimated.

A.10.7 References

California Regional Water Quality Control Board (CRWQCB), San Francisco Bay Region. 1985. Executive Officer Summary Report, Item 21: Fairchild, San Jose--Report on Proposal for Installation of Slurry Wall for Pollutant Containment, July 17.

California Regional Water Quality Control Board (CRWQCB), San Francisco Bay Region. No date. Order No. 82-61, NPDES No. CA0028185, Waste Discharge Requirements for Fairchild Camera and Instrument Corp., Bernal Road, San Jose, Santa Clara County.

Canonie Engineers. 1985. Progress Report: Aquifer "A" Flushing Program, March 8 through December 31, 1984, Fairchild Plant, San Jose, California.

Levine, J. D. 1981. Fact Sheet: Fairchild Semiconductor Waste Solvent Leakage From Underground Storage Tank. California Regional Water Quality Control Board, San Francisco Bay Region December 16.

Index

Active vapor control, 5-92 to 5-94
Adsorption, 5-95, 5-96
Air stripping, 5-5 to 5-61
Aqueous waste treatment, 5-14

Barrier materials, 2-3
Biological treatment, 5-63 to 5-68
Biostimulation, 5-50, 5-52 to 5-55

Capillary zone, 3-8 to 3-10
Carbon absorption, 5-61 to 5-63
Case studies
  Biocraft Laboratories, Waldwick, NJ, A-22
  Bulk Fuel Storage and Distribution Center, A-15
  Chemical Pipeline, A-19
  Fairchild Camera and Instrument Corp., South San Jose, California, A-30
  Gasoline Pipeline, Amber, Pennsylvania, A-3
  Gasoline Pipeline, Glendale, California, A-1
  Midwestern Laboratory Facility, A-17
  Retail Gasoline Station, Genesee County, Michigan, A-4
  Retail Gasoline Station, Montgomery County, Pennsylvania, 4-6
  U.S. Coast Guard Air Station, Traverse City, Michigan, A-10
Central water supplies
  alternatives to, 5-11
  treatment of, 5-112
Chemical treatment, 5-55 to 5-58
Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), 1-1
Containment migration
  through unsaturated (vadose) zone, 3-8, 3-9
  through saturated zone, 3-11
  through capillary zone, 3-9, 3-10
  transport in vapor phase, 3-11
Containment systems
  comparison of, 2-6
Control water supplies
  treatment of, 5-112
  alternative supplies, 5-110, 5-111
Corrective actions (initial)
  evaluation of release, 4-1
  determination of substance, 4-2, 4-3
  site characterization 4-2, 4-4 to 4-6
Corrective actions (permanent)
  assessment of land use and potential health impact,4-6
  human health and environmental factors affecting, 4-9
  institutional (regulatory) factors affecting, 4-9
  technical factors affecting, 4-9
Costs
  Active vapor-control systems, 5-94
  Air stripping, 5-60, 5-61
  Alternative central water supplies, 5-111
  Alternative point-of-use water supplies, 5-113
  Biological treatment, 5-67, 5-68
  Biostimulation, 5-55
  Capping, 5-105, 5-106
  Carbon adsorption, 5-63
  Chemical treatment, 5-57, 5-58
  Completion of 2- to 4-inch diameter wells, 5-32
  Deep-well injection, 5-15
  Dissolved air flotation, 5-73
  Diversion/collection systems, 5-101, 5-102, 5-103
  Dual-pump systems, 5-17
  Flaring, 5-97
  Floating-filter pumps, 5-18
  Grading, 5-104
  Granular media filtration, 5-75
  Ground-water pumping, 5-30
  Grouting, 5-47
  Hydaulic barriers, 5-49
  Interceptor drains, 5-43
  Ion exchange/resin adsorption, 5-76, 5-77
  Landfarming, 5-11
  Landfilling, 5-11
  Manholes, 5-43
  Neutralization, 5-79
  Oxidation/reduction, 5-78
  Packed-column aeration, 5-61
  Passive collection systems, 5-92
  Permanent corrective actions, 4-9
  Physical treatment, 5-58
  Pipe installation, 5-42
  Precipitation/flocculation/sedimentation, 5-71, 5-72
  Product recovery costs, 5-17
  Revegetation, 5-108, 5-109, 5-110
  Reverse osmosis, 5-82, 5-83, 5-84
  Selected pumps and accessories, 5-31
  Seven recovery system cost scenarios, 5-33
  Sheet piles, 5-48
  Sludge dewatering, 5-88, 5-89
  Slurry walls, 5-46

Costs (continued)
  Soil flushing, 5-52
  Soil washing, 5-12
  Solidification/stabilization, 5-9, 5-10
  Steam stripping, 5-81
  Subsurface drains, 5-38, 5-39
  Surface oil/water separators, 5-19
  Thermal destruction, 5-14
  Treatment of central water supplies, 5-112
  Treatment of point-of-use water supplies, 5-113
  Trench Excavation, 5-40, 5-41
  Ventilation structures, 5-96
  Water and sewer lines
    replacement, 5-113
    cleaning/restoration, 5-115
  Well screens and well points, 5-32

Deep well injection, 5-14, 5-15
Dissolved air flotation, 5-72, 5-73
Diversion/collection systems
  dikes and berms, 5-98, 5-99
  channels and waterways, 5-99, 5-100
  chutes and downpipes, 5-99, 5-100
  sedimentation basins and ponds, 5-99, 5-101
  seepage basins and ditches, 5-99, 5-100
  terraces and benches, 5-99, 5-100
Downhole turbine, 5-27
Drainage controls (*see surface water*)
Dredging
  mechanical, 5-7
  hydraulic, 5-7, 5-8
Dual-pump systems 5-16, 5-17

Fiberglass-reinforced plastic (FRP) tanks
  description of 2-2, 2-5, 2-6
Floating-filter pumps, 5-18
Flaring, 5-96, 5-97

Grading, 5-101, 5-104
Granular media filtration, 5-73 to 5-75
Ground-water pumping, 5-20 to 5-22
Ground-water recovery
  ground-water pumping (*see above*)
  subsurface drains, 5-34
Grouting, 5-46, 5-47

Hydraulic barriers, 5-48, 5-49

Incineration technologies, 5-13, 5-14
In situ treatment (*see biostimulation, chemical treatment, physical treatment, soil flushing*)
Interceptor drains, 5-36, 5-43
Inventory control, 3-1
Ion exchange/resin adsorption, 5-75 to 5-77

Landfarming, 5-11
Landfilling, 5-9 to 5-11

Leaks
  causes of, 2-5
Leak detection methods
  inventory control, 3-1, 3-2
  monitoring, 3-7
  nonvolumetric, 3-1, 3-2, 3-4
  other, 3-5, 3-6
  variables affecting accuracy, 3-7
  volumetric, 3-1, 3-2, 3-3

Onsite and offsite treatment and disposal of contaminants, 4-4, 5-8
Oxidation/reduction, 5-77, 5-78

Passive collection systems, 5-90 to 5-92
Physical treatment, 5-58
Piping systems
  causes of pipe failure, 2-5
  leaks, 2-5
Point-of-use water supplies
  alternatives to, 5-111, 5-112
  treatment of, 5-112, 5-113
Precipitation/flocculation/desimentation, 5-68 to 5-72
Pumping (*see ground-water pumping*)

Redox (see oxidation/reduction)
Rehabilitation of tanks, 5-4
Released substances
  chemical and physical characteristics of, 4-2
Removal of tanks, 5-5
  soil excavation, 5-6
  sediment removal, 5-7
Resource Conservation and Recovery Act (RCRA)
Subtitle 1
  definition of, 1-1
Reverse osmosis, 5-81 to 5-84
Risk evaluation, 4-9
  analysis, 4-9
  exposure assessments, 4-6
  hazard evaluations, 4-9
  risk assessments, 4-7

Sampling points (existing) 3-12, 3-13
  inventory records, 3-12
  surface water bodies, 3-13
  underground structure, 3-12
  water supply wells, 3-12
Sampling points (new), 3-13
  accumulator devices, 3-13
  downhole flux chambers, 3-13
  ground probes, 3-13
  soil borings, 3-15
  surface flux chambers, 3-15
Saturated zone, 3-11
Sediment removal, 5-7
Sewer lines (*see water lines*)
Sheet piles, 5-47, 5-48
Site characterization, 4-2

Site characterization (continued)
  geography/topography, 4-4, 4-6
  hydrogeology, 4-2, 4-4
  water and land use patterns, 4-4, 4-6
Sludge dewatering
  filter press dewatering, 5-84, 5-85, 5-88, 5-89
  belt filter dewatering, 5-85, 5-86, 5-88, 5-89
  centrifugal dewatering, 5-86, 5-88
  vacuum filtration, 5-84, 5-88, 5-89
Slurry trench, 5-44
Slurry walls, 5-39 to 5-46
Soil flushing, 5-50 to 5-52
Soil washing, 5-11, 5-12
Solidification/stabilization, 5-8, 5-9, 5-10
Steam stripping, 5-79 to 5-81
Submersible pump, 5-25
Subsurface barriers (*see grouting, hydraulic barriers, sheet piles, slurry walls*)
Subsurface drains, 5-34
  location and spacing of, 5-35
  filters and envelopes, 5-35
Surface oil/water separators, 5-18, 5-19
Surface water/drainage controls
  capping, 5-104
  diversion/collection systems, 5-98
  grading, 5-101
  revegetation, 5-105

Thermal destruction, 5-12 to 5-14

Underground storage tanks (*USTs*)
  types, 2-1
  substances stored, 4-2, 4-3
Unsaturated zone (*see vadose zone*)

Vadose zone, 3-8, 3-9
Vapor mitration control, collection, and treatment
  active collection systems, 5-90
  adsorption, 5-95
  flaring 5-96
  passive collection systems, 5-90
  ventilation of structures, 5-94
Vapor phase, 3-11
Volumetric leak detection, 3-1, 3-2, 3-3

Waterlines/sewerlines
  cleaning of, 5-114, 5-115
  replacement of, 5-113
  restoration after contamination, 5-114, 5-115
Well point systems, 5-22, 5-24, 5-25
Wells
  drilled, 5-28 to 5-30
  driven, 5-28, 5-29
  ejector, 5-27
  extraction, 5-21
  injection, 5-15, 5-21, 5-22
  jetted, 5-28, 5-29
  suction lift, 5-24
Well screens, 5-32

✩ U.S. GOVERNMENT PRINTING OFFICE: 1987-748-121/40695